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SMEFT effects in neutrino and low-energy experiments

HEFT in Bologna
13 June 2024

Based on [arXiv:1901.04553], [arXiv:1910.02871] with Martin Gonzalez-Alonso, Zahra Tabrizi, [arXiv:2207.02161] with Antonio Rodriguez-Sanchez, and on [arXiv:2301.07036] Victor Breso-Pla, Martin Gonzalez-Alonso, Kevin Monsalvez-Pozo

Plan

<u>Focus:</u> constraints on SMEFT from processes where neutrinos are detected

- Neutrinos and SMEFT
- Constraints from coherent neutrino scattering
- Constraints from reactor neutrino oscillations
- Constraints on CP violation in nuclear beta decay

SMEFT

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \cdots \\ v + h + \dots \end{pmatrix}$$

SMEFT has many higher-dimensional operators:

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

Neutrinos enter into a non-negligible fraction of these

Constraints from neutrino physics are essential to sharpen the phenomenological constraints on SMEFT Wilson coefficients

SMEFT at dimension-5

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

Weinberg (1979)
Phys. Rev. Lett. 43, 1566

$$H \to \begin{pmatrix} 0 \\ \mathrm{v}/\sqrt{2} \end{pmatrix}$$

$$\mathscr{L}_{D=5} = (LH)C_5(LH) + \text{h.c.} \to \frac{1}{2} \sum_{J,K=e,\mu,\tau} \mathrm{v}^2 [C_5]_{JK} (\nu_J \nu_K) + \text{h.c.}$$

Dimension 5 operators in SMEFT lead to neutrino masses. The corresponding Wilson coefficients are probed (only) by neutrino oscillations experiments

$$-\mathrm{v}^2 C_5 = U_{\text{PMNS}} m_{\text{diag}} U^\dagger_{\text{PMNS}}$$

$$m_{\text{diag}} = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

All these parameters known with good accuracy (up to ordering ambiguity), except for m_1 and δ_{CP}

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & e^{-i\delta_{\text{CP}}}s_{13} \\ -s_{12}c_{23} - e^{i\delta_{\text{CP}}}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta_{\text{CP}}}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta_{\text{CP}}}c_{12}s_{13}c_{23} & -c_{12}s_{23} - e^{i\delta_{\text{CP}}}s_{12}s_{13}c_{23} & c_{13}c_{23} \end{pmatrix}$$

SMEFT at dimension-6

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

Grządkowski et al
arXiv:1008.4884

At dimension-6 all hell breaks loose

$$\mathscr{L}_{D=6} = C_H (H^\dagger H)^3 + C_{H\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD}|H^\dagger D_\mu H|^2$$

$$+C_{HWB} H^\dagger \sigma^k H\, W^k_{\mu\nu} B_{\mu\nu} + C_{HG} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu} + C_{HW} H^\dagger H\, W^k_{\mu\nu} W^k_{\mu\nu} + C_{HB} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$$

$$++C_W \epsilon^{klm} W^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu} + C_G f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$$

$$+C_{H\widetilde{G}} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu} + C_{H\widetilde{W}} H^\dagger H\, \widetilde{W}^k_{\mu\nu} W^k_{\mu\nu} + C_{H\widetilde{B}} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu} + C_{H\widetilde{W}B} H^\dagger \sigma^k H\, \widetilde{W}^k_{\mu\nu} B_{\mu\nu}$$

$$+C_{\widetilde{W}} \epsilon^{klm} \widetilde{W}^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu} + C_{\widetilde{G}} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$$

$$+H^\dagger H(\bar{L} H C_{eH} \bar{E}^c) + H^\dagger H(\bar{Q}\tilde{H} C_{uH} \bar{U}^c) + H^\dagger H(\bar{Q} H C_{dH} \bar{D}^c)$$

$$+iH^\dagger \overleftrightarrow{D}_\mu H(\bar{L} C^{(1)}_{Hl} \bar{\sigma}^\mu L) + iH^\dagger \sigma^k \overleftrightarrow{D}_\mu H(\bar{L} C^{(3)}_{Hl} \bar{\sigma}^\mu \sigma^k L) + iH^\dagger \overleftrightarrow{D}_\mu H(E^c C_{He} \sigma^\mu \bar{E}^c)$$

$$+iH^\dagger \overleftrightarrow{D}_\mu H(\bar{Q} C^{(1)}_{Hq} \bar{\sigma}^\mu Q) + iH^\dagger \sigma^k \overleftrightarrow{D}_\mu H(\bar{Q} C^{(3)}_{Hq} \bar{\sigma}^\mu \sigma^k Q) + iH^\dagger \overleftrightarrow{D}_\mu H(U^c C_{Hu} \sigma^\mu \bar{U}^c)$$

$$+iH^\dagger \overleftrightarrow{D}_\mu H(D^c C_{Hd} \sigma^\mu \bar{D}^c) + \Big\{ i\tilde{H}^\dagger D_\mu H(U^c C_{Hud} \sigma^\mu \bar{D}^c)$$

$$+(\bar{Q}\sigma^k \tilde{H} C_{uW} \bar{\sigma}^{\mu\nu} \bar{U}^c) W^k_{\mu\nu} + (\bar{Q}\tilde{H} C_{uB} \bar{\sigma}^{\mu\nu} \bar{U}^c) B_{\mu\nu} + (\bar{Q}\tilde{H} C_{uG} T^a \bar{\sigma}^{\mu\nu} \bar{U}^c) G^a_{\mu\nu}$$

$$+(\bar{Q}\sigma^k H C_{dW} \bar{\sigma}^{\mu\nu} \bar{D}^c) W^k_{\mu\nu} + (\bar{Q} H C_{dB} \bar{\sigma}^{\mu\nu} \bar{D}^c) B_{\mu\nu} + (\bar{Q} H C_{dG} T^a \bar{\sigma}^{\mu\nu} \bar{D}^c) G^a_{\mu\nu}$$

$$+(\bar{L}\sigma^k H C_{eW} \bar{\sigma}^{\mu\nu} \bar{E}^c) W^k_{\mu\nu} + (\bar{L} H C_{eB} \bar{\sigma}^{\mu\nu} \bar{E}^c) B_{\mu\nu} + \mathrm{h.c.} \Big\} + \mathscr{L}^{4-\rm fermion}_{D=6}$$

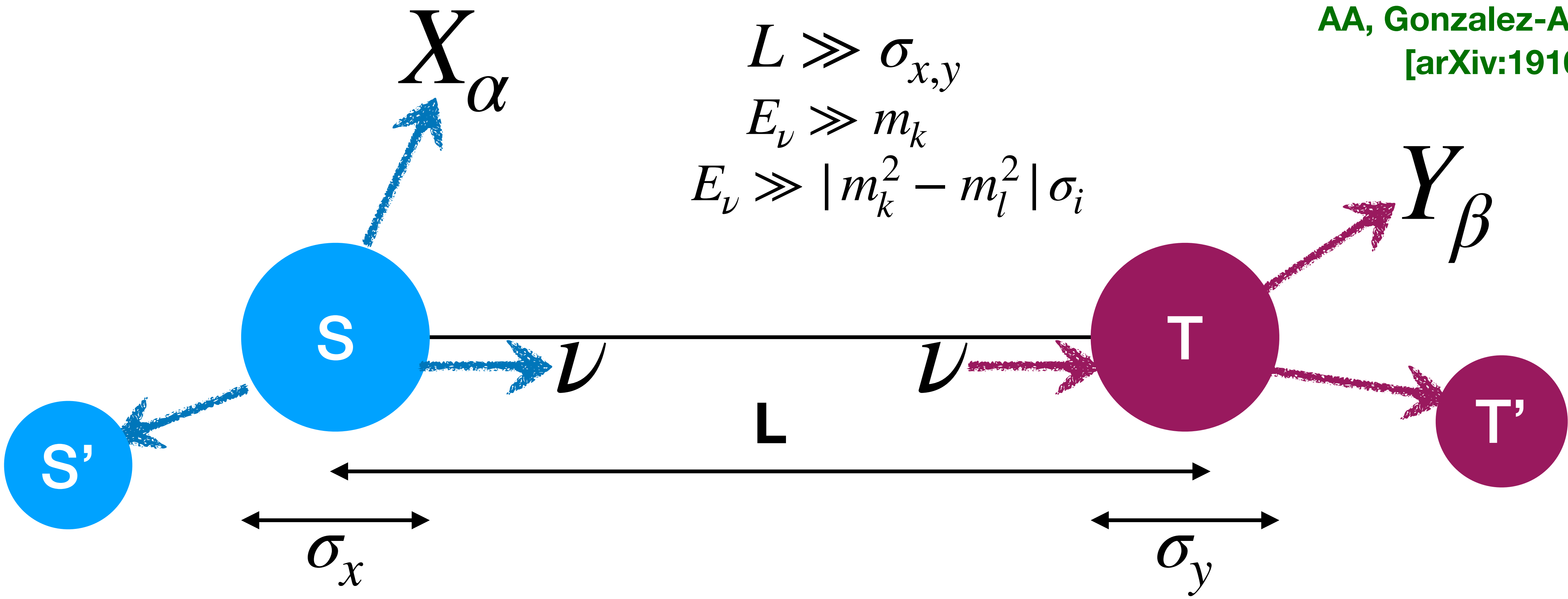
SMEFT at dimension-6

$$
\begin{aligned}
\mathscr{L}^{4-\text{fermion}}_{D=6} = & (\bar{L}\bar{\sigma}^\mu L)C_{ll}(\bar{L}\bar{\sigma}_\mu L) + (E^c\sigma_\mu\bar{E}^c)C_{ee}(E^c\sigma_\mu\bar{E}^c) + (\bar{L}\bar{\sigma}^\mu L)C_{le}(E^c\sigma_\mu\bar{E}^c) \\
& +(\bar{L}\bar{\sigma}^\mu L)C^{(1)}_{lq}(\bar{Q}\bar{\sigma}_\mu Q) + (\bar{L}\bar{\sigma}^\mu\sigma^k L)C^{(3)}_{lq}(\bar{Q}\bar{\sigma}_\mu\sigma^k Q) \\
& +(E^c\sigma_\mu\bar{E}^c)C_{eu}(U^c\sigma_\mu\bar{U}^c) + (E^c\sigma_\mu\bar{E}^c)C_{ed}(D^c\sigma_\mu\bar{D}^c) \\
& +(\bar{L}\bar{\sigma}^\mu L)C_{lu}(U^c\sigma_\mu\bar{U}^c) + (\bar{L}\bar{\sigma}^\mu L)C_{ld}(D^c\sigma_\mu\bar{D}^c) + (E^c\sigma_\mu\bar{E}^c)C_{eq}(Q\bar{\sigma}_\mu Q) \\
& +\left\{ (\bar{L}\bar{E}^c)C_{ledq}(D^cQ) + \epsilon^{kl}(\bar{L}^k\bar{E}^c)C^{(1)}_{lequ}(\bar{Q}^l\bar{U}^c) + \epsilon^{kl}(\bar{L}^k\bar{\sigma}^{\mu\nu}\bar{E}^c)C^{(3)}_{lequ}(\bar{Q}^l\bar{\sigma}^{\mu\nu}\bar{U}^c) + \text{h.c.} \right\} \\
& +(\bar{Q}\bar{\sigma}^\mu Q)C^{(1)}_{qq}(\bar{Q}\bar{\sigma}_\mu Q) + (\bar{Q}\bar{\sigma}^\mu\sigma^k Q)C^{(3)}_{qq}(\bar{Q}\bar{\sigma}_\mu\sigma^k Q) \\
& +(U^c\sigma_\mu\bar{U}^c)C_{uu}(U^c\sigma_\mu\bar{U}^c) + (D^c\sigma_\mu\bar{D}^c)C_{dd}(D^c\sigma_\mu\bar{D}^c) \\
& +(U^c\sigma_\mu\bar{U}^c)C^{(1)}_{ud}(D^c\sigma_\mu\bar{D}^c) + (U^c\sigma_\mu T^a\bar{U}^c)C^{(8)}_{ud}(D^c\sigma_\mu T^a\bar{D}^c) \\
& +(Q^c\sigma_\mu\bar{Q}^c)C^{(1)}_{qu}(U^c\sigma_\mu\bar{U}^c) + (Q^c\sigma_\mu T^a\bar{Q}^c)C^{(8)}_{qu}(U^c\sigma_\mu T^a\bar{U}^c)] \\
& +(Q^c\sigma_\mu\bar{Q}^c)C^{(1)}_{qd}(D^c\sigma_\mu\bar{D}^c) + (Q^c\sigma_\mu T^a\bar{Q}^c)C^{(8)}_{qd}(D^c\sigma_\mu T^a\bar{D}^c) \\
& +\left\{ \epsilon^{kl}(\bar{Q}^k\bar{U}^c)C^{(1)}_{quqd}(\bar{Q}^l\bar{D}^c) + \epsilon^{kl}(\bar{Q}^kT^a\bar{U}^c)C^{(1)}_{quqd}(\bar{Q}^lT^a\bar{D}^c) + \text{h.c.} \right\} \\
& +\left\{ (D^cU^c)C_{duq}(\bar{Q}\bar{L}) + (QQ)C_{qqu}(\bar{U}^c\bar{E}^c) + (QQ)C_{qqq}(QL) + (D^cU^c)C_{duu}(U^cE^c) + \text{h.c.} \right\}.
\end{aligned}
$$

The highlighted operators can be probed by processes where neutrinos are produced, detected, or exchanged.
Very often, constraints from non-neutrino processes leave important degeneracies in the space of corresponding Wilson coefficients.

Neutrino master formula

AA, Gonzalez-Alonso, Tabrizi [arXiv:1910.02971]



$$dR_{\alpha\beta} = \frac{N_S N_T}{32\pi L^2 m_S m_T} \sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}\right) \left[d\Pi_P \mathcal{M}^P_{\alpha k} \mathcal{M}^{P*}_{\alpha l}\right] \left[d\Pi_D \mathcal{M}^D_{\beta k} \mathcal{M}^{D*}_{\beta l}\right]$$

Observable rate $dR = \frac{dN}{dt}$

Geometric factor

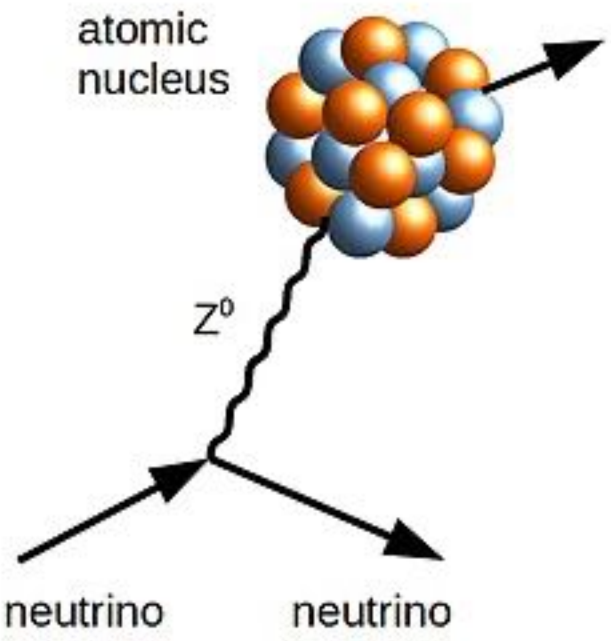
Masses of source and target atoms

Oscillation phase

Production phase space $\mathcal{M}^P_{\alpha k} \equiv \mathcal{M}[S \to S' X_\alpha \nu_k]$

Detection phase space $\mathcal{M}^D_{\beta k} \equiv \mathcal{M}[\nu_k T \to T' Y_\beta]$

Part 2



Constraints from coherent neutrino scattering

Coherent neutrino scattering

- Coherent neutrino scattering occurs when neutrino scattering on a nucleus has low enough energy such that it does not resolve its internal structure. Then $\sim (A-Z)^2$ enhancement of the cross section occurs.

D. Freedman, Phys. Rev. D 9 (1974) 1389–1392

- Experimentally measured recently by the COHERENT collaboration with neutrino produced by stopped pion decays and with Argon and CsI targets.

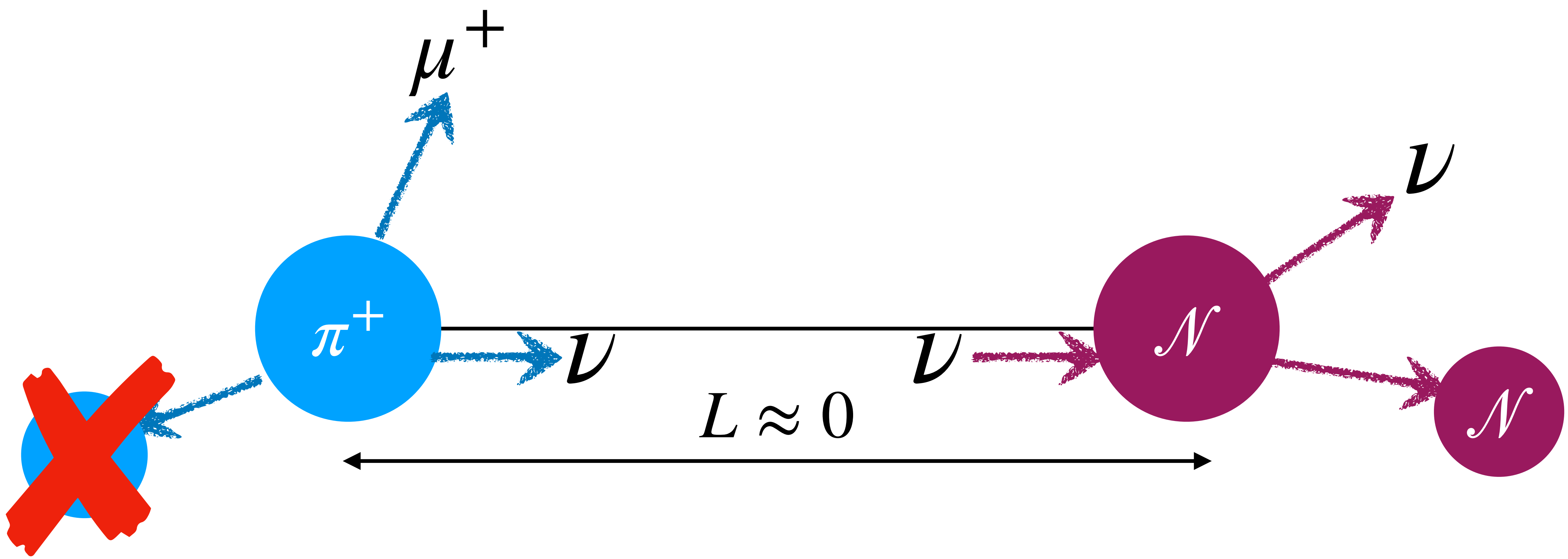
COHERENT, Science 357 [arXiv:1708.01294]

COHERENT, Phys. Rev. Lett. 126 [arXiv:2003.10630]

COHERENT, Phys. Rev. Lett. 129 [arXiv:2110.07730].

- Time and nuclear recoil distributions are available. Neutrinos from the pion decay and from the subsequent muon decay can be disentangled thanks to timing. Neutrinos and anti-neutrinos from muon decay can also be to some extent disentangled thanks to different recoil distributions.

Coherent neutrino scattering



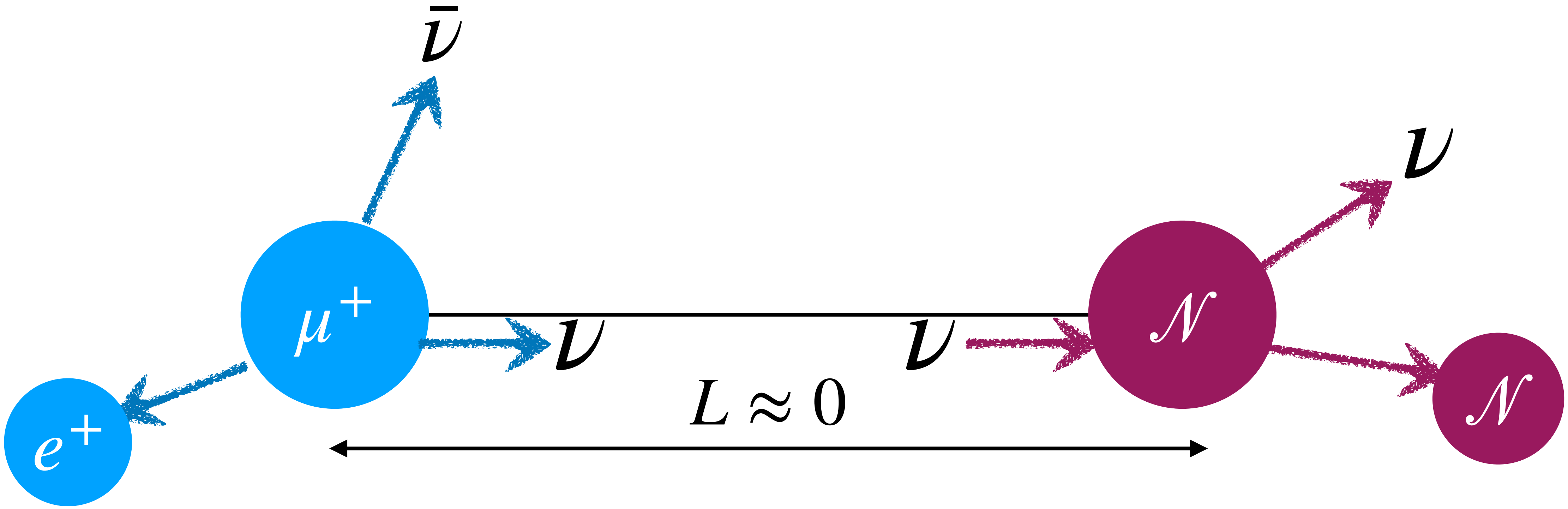
$$dR_\mu^{\text{prompt}} = \frac{N_S N_T}{32\pi L^2 m_\pi m_{\mathcal{N}}} \sum_{k,l=1}^{3} e^{-i\frac{(m_k^2 - m_l^2)L}{2E_\nu}} \left[d\Pi_P \mathscr{M}^P_{\mu k} \mathscr{M}^{P*}_{\mu l}\right] \sum_\beta \left[d\Pi_D \mathscr{M}^D_{\beta k} \mathscr{M}^{D*}_{\beta l}\right]$$

Negligible in COHERENT setup

$\mathscr{M}^P_{\alpha k} \equiv \mathscr{M}[\pi^+ \to \mu^+ \nu_k]$

$\mathscr{M}^D_{\beta k} \equiv \mathscr{M}[\nu_k \mathcal{N} \to \nu_\beta \mathcal{N}]$

Coherent neutrino scattering



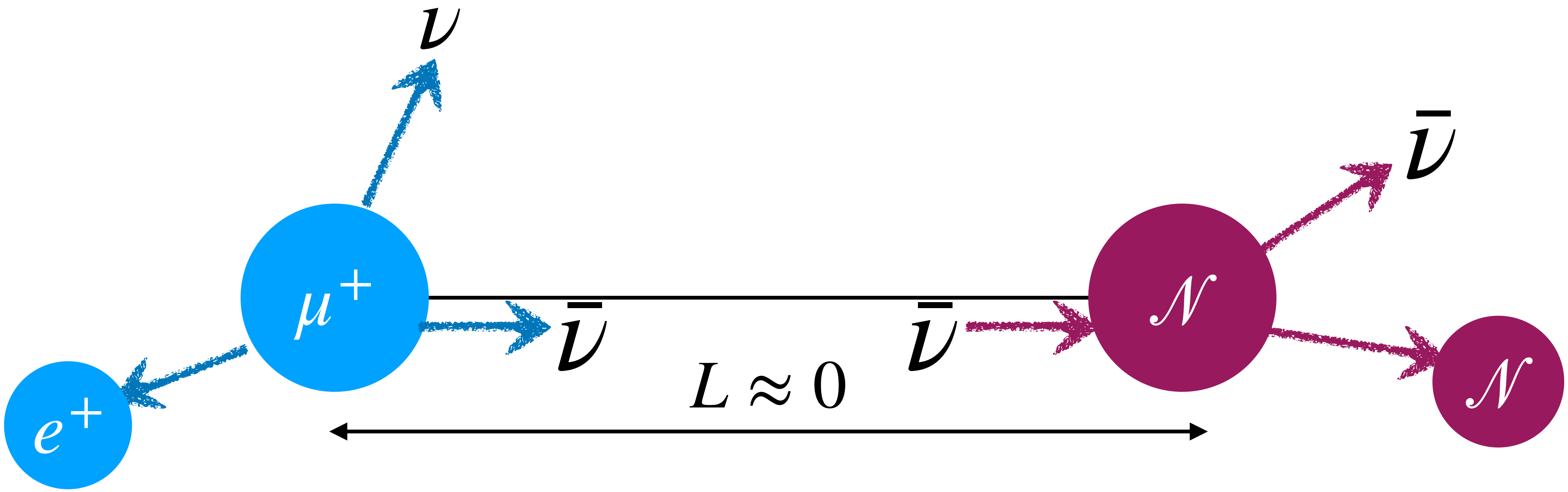
$$dR_\mu^{\text{delayed}} = \frac{N_S N_T}{32\pi L^2 m_\mu m_{\mathscr{N}}} \sum_{k,l=1}^{3} e^{-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}} \left[d\Pi_P \mathscr{M}^P_{\mu k} \mathscr{M}^{P*}_{\mu l}\right] \sum_\beta \left[d\Pi_D \mathscr{M}^D_{\beta k} \mathscr{M}^{D*}_{\beta l}\right]$$

Negligible in COHERENT setup

$\mathscr{M}^P_{\alpha k} \equiv \mathscr{M}[\mu^+ \to e^+ \nu_k \bar{\nu}]$

$\mathscr{M}^D_{\beta k} \equiv \mathscr{M}[\nu_k \mathscr{N} \to \nu_\beta \mathscr{N}]$

Coherent neutrino scattering



$$d\bar{R}_\mu^{\text{delayed}} = \frac{N_S N_T}{32\pi L^2 m_\mu m_{\mathcal{N}}} \sum_{k,l=1}^{3} e^{-i\frac{(m_k^2 - m_l^2)L}{2E_\nu}} \left[d\Pi_P \mathcal{M}_{\mu k}^{P} \mathcal{M}_{\mu l}^{P*}\right] \sum_\beta \left[d\Pi_D \mathcal{M}_{\beta k}^{D} \mathcal{M}_{\beta l}^{D*}\right]$$

Negligible in COHERENT setup

$\mathcal{M}_{\alpha k}^{P} \equiv \mathcal{M}[\mu^+ \to e^+ \bar{\nu}_k \nu]$

$\mathcal{M}_{\beta k}^{D} \equiv \mathcal{M}[\bar{\nu}_k \mathcal{N} \to \bar{\nu}_\beta \mathcal{N}]$

Coherent neutrino scattering

After integrating over phase space, one can rewrite the rate in the form

$$\frac{dR^{\text{prompt}}}{dT} = N_T \int dE_\nu \frac{d\Phi_{\nu_\mu}}{dE_\nu} \frac{d\tilde{\sigma}_{\nu_\mu}}{dT}$$

$$\frac{dR^{\text{delayed}}}{dT} = N_T \int dE_\nu \left(\frac{d\Phi_{\nu_e}}{dE_\nu} \frac{d\tilde{\sigma}_{\nu_e}}{dT} + \frac{d\Phi_{\bar{\nu}_\mu}}{dE_\nu} \frac{d\tilde{\sigma}_{\bar{\nu}_\mu}}{dT} \right)$$

recoil kinetic energy of nucleus

$$\frac{d\phi_{\nu_\mu}}{dE_\nu} = \frac{N_S}{4\pi L^2} \delta(E_\nu - E_{\nu,\pi})$$

$$\frac{d\phi_{\nu_e}}{dE_\nu} = \frac{N_S}{4\pi L^2} \frac{192 E_\nu^2}{m_\mu^3} \left(\frac{1}{2} - \frac{E_\nu}{m_\mu} \right)$$

$$\frac{d\phi_{\bar{\nu}_\mu}}{dE_\nu} = \frac{N_S}{4\pi L^2} \frac{64 E_\nu^2}{m_\mu^3} \left(\frac{3}{4} - \frac{E_\nu}{m_\mu} \right)$$

The effective cross sections are

Nuclear form factor

$$\frac{d\tilde{\sigma}_{\nu_f}}{dT} = (m_{\mathcal{N}} + T) \frac{(\mathscr{F}(T))^2}{8 \mathrm{v}^4 \pi} \left(1 - \frac{(m_{\mathcal{N}} + 2E_\nu)\, T}{2E_\nu^2} \right) \tilde{Q}_f^2 \, .$$

The effective weak charges encode full information about new physics corrections, both in production and in detection

$$\tilde{Q}_f^2 = Q_{\text{SM}}^2 + \Delta_f(C_i)$$

$\sim (Z - A)^2$

Coherent neutrino scattering

Results of our analysis for effective weak charges

V. Breso-Pla et al [arXiv:2301.07036]

$$\begin{pmatrix} \tilde{Q}_\mu^2 \\ \tilde{Q}_{\bar{\mu}}^2 \\ \tilde{Q}_e^2 \end{pmatrix}_{\rm Ar} \frac{1}{Q^2_{\rm SM,Ar}} = \begin{pmatrix} 1.00 \pm 0.82 \\ 0.4 \pm 6.2 \\ 1.9 \pm 8.2 \end{pmatrix} \qquad \rho = \begin{pmatrix} 1 & 0.29 & -0.31 \\ 0.29 & 1 & -0.99 \\ -0.31 & -0.99 & 1 \end{pmatrix} \qquad Q^2_{\rm SM,Ar} \approx 461$$

$$\begin{pmatrix} \tilde{Q}_\mu^2 \\ \tilde{Q}_{\bar{\mu}}^2 \\ \tilde{Q}_e^2 \end{pmatrix}_{\rm CsI} \frac{1}{Q^2_{\rm SM,CsI}} = \begin{pmatrix} 1.33 \pm 0.35 \\ -1.4 \pm 1.5 \\ 4.4 \pm 2.3 \end{pmatrix} \qquad \rho = \begin{pmatrix} 1 & 0.12 & -0.09 \\ 0.12 & 1 & -0.98 \\ -0.09 & -0.98 & 1 \end{pmatrix} \qquad Q^2_{\rm SM,CsI} \approx 5572$$

A more intuitive form

$$\begin{pmatrix} -0.14 & -3.48 & 4.62 \\ -0.69 & 0.98 & 0.71 \\ 0.55 & 0.25 & 0.20 \end{pmatrix} \begin{pmatrix} \tilde{Q}_\mu^2 \\ \tilde{Q}_{\bar{\mu}}^2 \\ \tilde{Q}_e^2 \end{pmatrix}_{\rm Ar} \frac{1}{Q^2_{\rm SM,Ar}} = \begin{pmatrix} 6 \pm 59 \\ \mathbf{1.0 \pm 1.2} \\ \mathbf{1.03 \pm 0.48} \end{pmatrix}$$

$$\begin{pmatrix} -0.04 & -1.80 & 2.85 \\ 0.80 & 0.12 & 0.09 \\ -0.15 & 0.71 & 0.45 \end{pmatrix} \begin{pmatrix} \tilde{Q}_\mu^2 \\ \tilde{Q}_{\bar{\mu}}^2 \\ \tilde{Q}_e^2 \end{pmatrix}_{\rm CsI} \frac{1}{Q^2_{\rm SM,CsI}} = \begin{pmatrix} 15.1 \pm 9.1 \\ \mathbf{1.28 \pm 0.28} \\ \mathbf{0.81 \pm 0.19} \end{pmatrix}$$

Coherent neutrino scattering

Translation into SMEFT constraints

V. Breso-Pla et al [arXiv:2301.07036]

$$\mathcal{L}_{\rm SMEFT} \supset C_{lq}^{(1)}(\bar{l}_L\gamma_\mu l_L)(\bar{q}_L\gamma^\mu q_L) + C_{lq}^{(3)}(\bar{l}_L\gamma_\mu\sigma^k l_L)(\bar{q}_L\gamma^\mu\sigma^k q_L)$$
$$+C_{lu}(\bar{l}_L\gamma_\mu l_L)(\bar{u}_R\gamma^\mu u_R) + C_{ld}(\bar{l}_L\gamma_\mu l_L)(\bar{d}_R\gamma^\mu d_R).$$

Ignoring quadratic corrections in Wilson coefficients one gets the constraints

$$\begin{pmatrix} 0.63 & -0.70 & -0.22 & 0.24 \\ 0.21 & -0.24 & 0.63 & -0.70 \\ -0.68 & -0.61 & 0.30 & 0.27 \\ 0.30 & 0.27 & 0.68 & 0.61 \end{pmatrix} \begin{pmatrix} \epsilon_{ee}^{dd} \\ \epsilon_{ee}^{uu} \\ \epsilon_{\mu\mu}^{dd} \\ \epsilon_{\mu\mu}^{uu} \end{pmatrix} = \begin{pmatrix} 2.0 \pm 5.7 \\ -0.2 \pm 1.7 \\ -0.037 \pm 0.042 \\ -0.004 \pm 0.013 \end{pmatrix}$$

$$\epsilon_{\alpha\alpha}^{uu} = \delta g_L^{Zu} + \delta g_R^{Zu} + \left(1 - \frac{8s_\theta^2}{3}\right)\delta g_L^{Z\nu_\alpha} - \frac{1}{2}[c_{lq}^{(1)} + c_{lq}^{(3)} + c_{lu}]_{\alpha\alpha 11}$$

$$c_X \equiv C_X \mathrm{v}^2$$

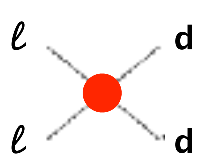
$$\epsilon_{\alpha\alpha}^{dd} = \delta g_L^{Zd} + \delta g_R^{Zd} - \left(1 - \frac{4s_\theta^2}{3}\right)\delta g_L^{Z\nu_\alpha} - \frac{1}{2}[c_{lq}^{(1)} - c_{lq}^{(3)} + c_{ld}]_{\alpha\alpha 11}$$

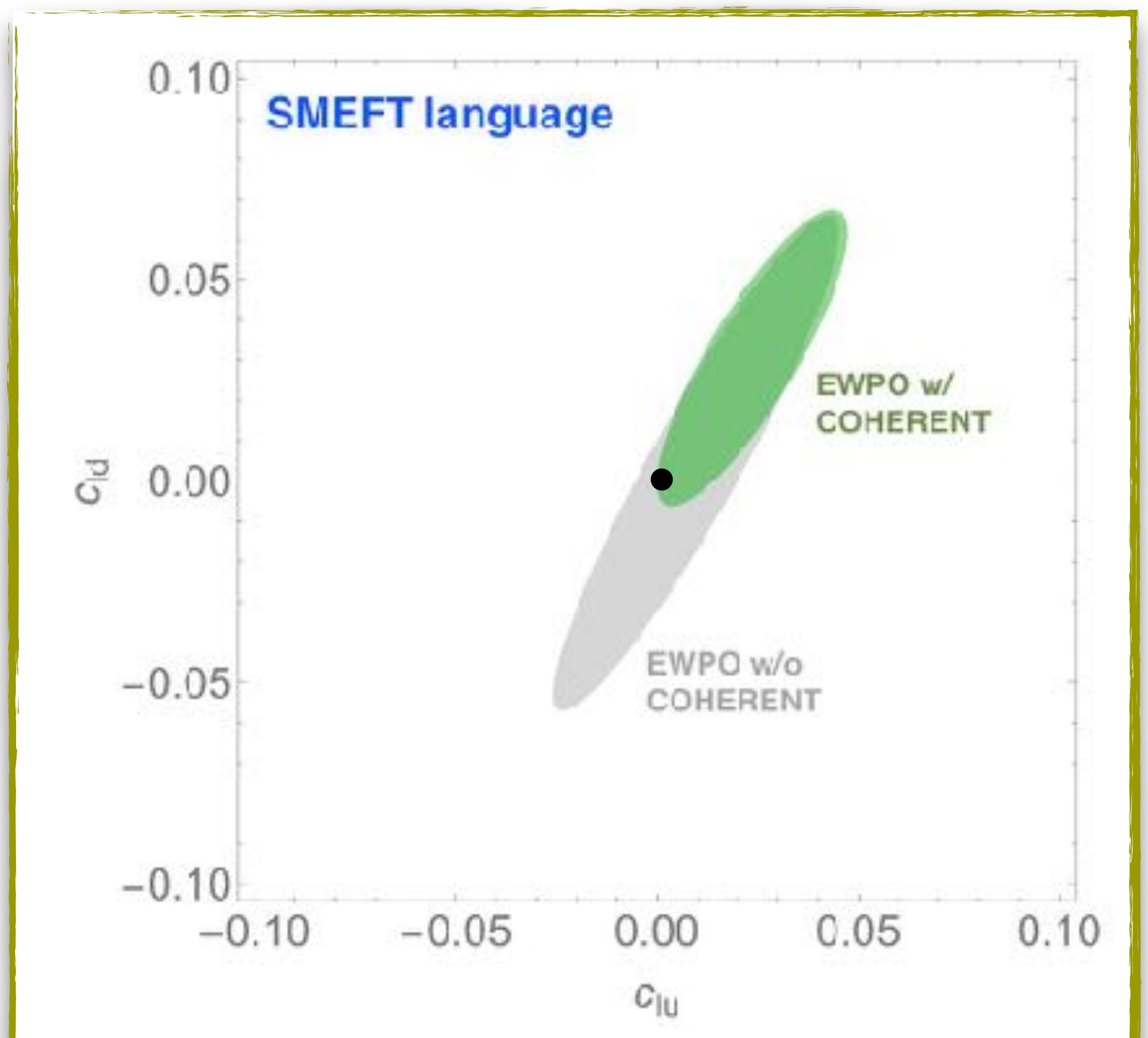
- **Only 4 constraints and not 6 because one can show that, at linear order in new physics, there are only two independent charges per nucleus, that is $\tilde{Q}_\mu = \tilde{Q}_{\bar{\mu}}$**
- **Only two combination of SMEFT parameters are efficiently constrained, at the percent level**

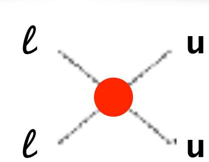
Coherent neutrino scattering

Combination of COHERENT constraints with other low- and high-energy electroweak precision tests

Assuming flavor symmetric $(U(3)^5)$ Wilson coefficients one see O(1) improvement in some constraints





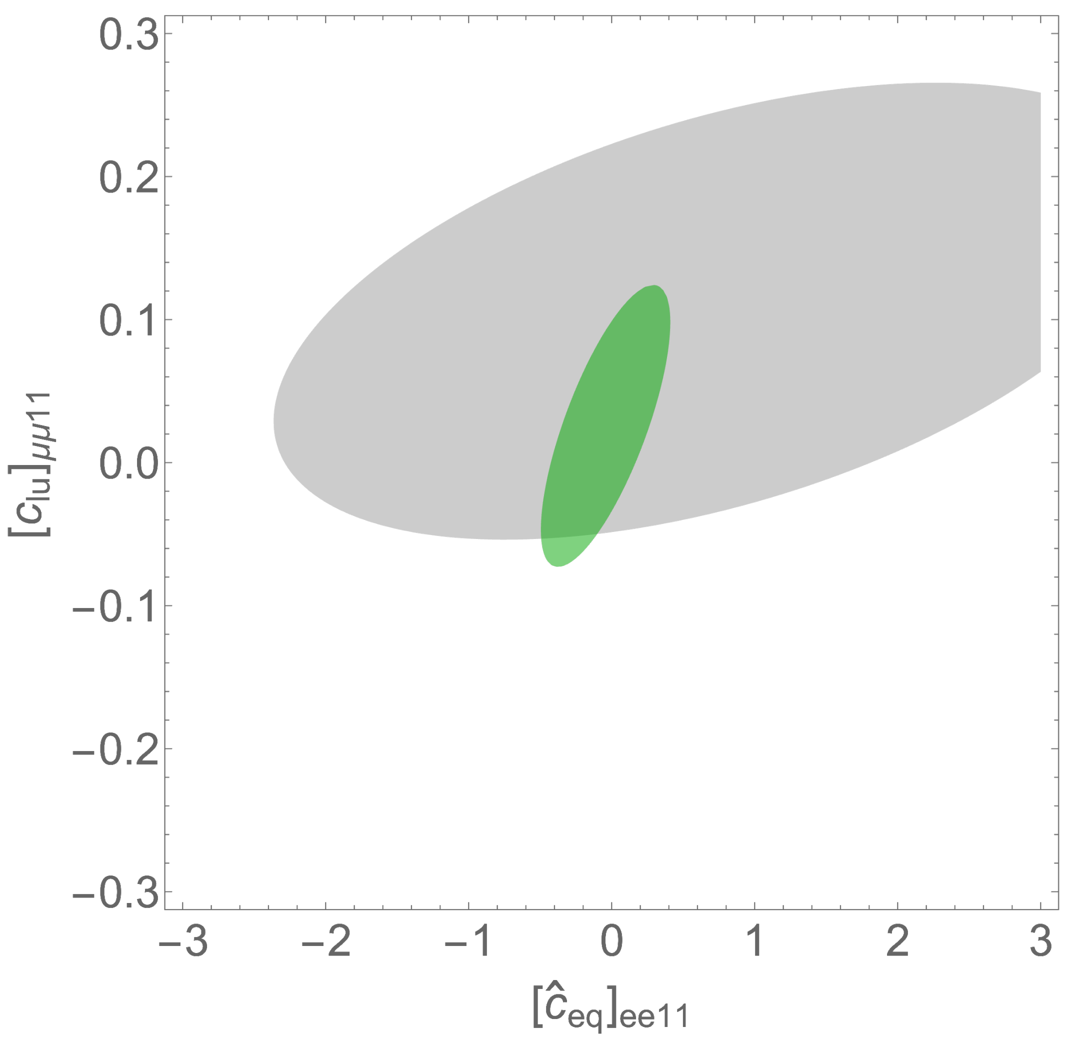


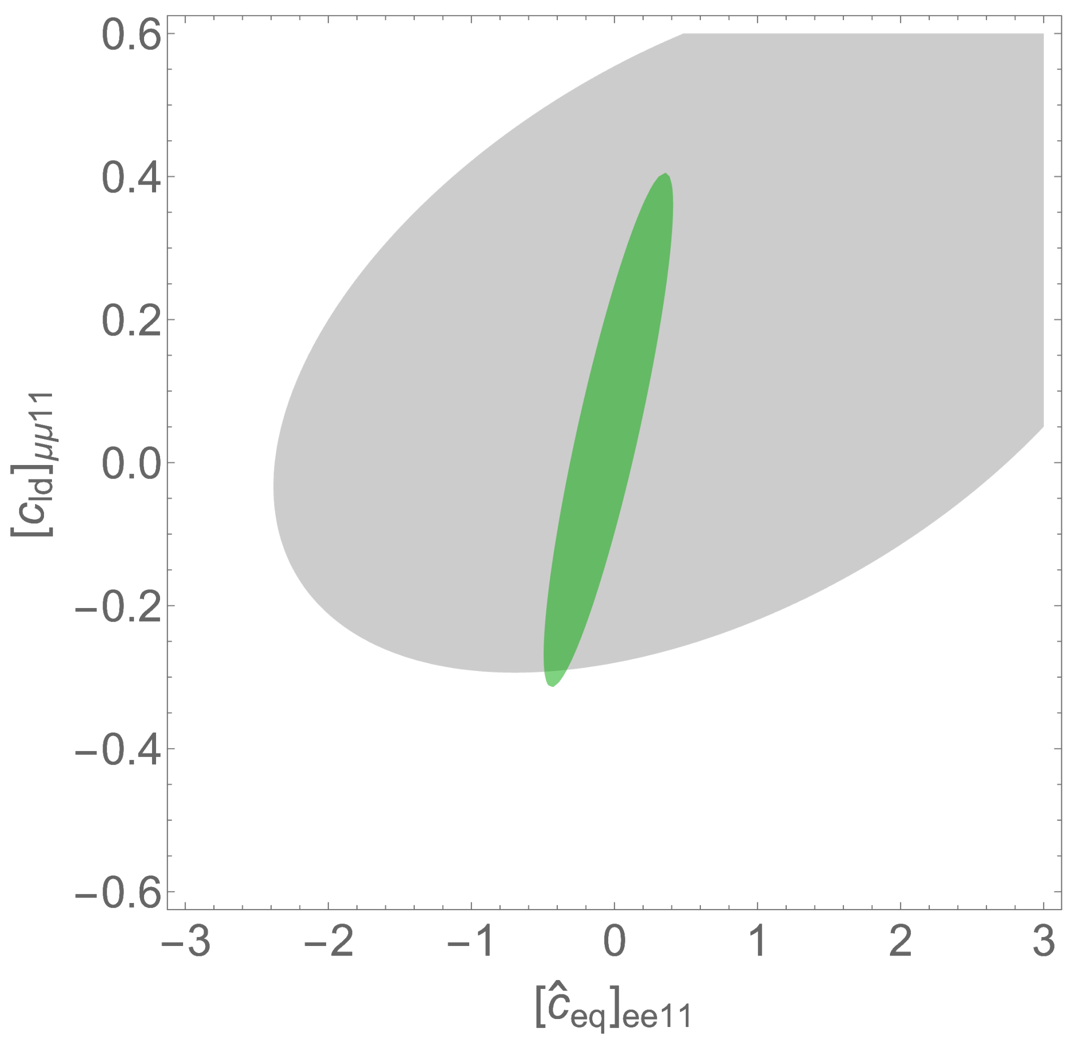
V. Breso-Pla et al [arXiv:2301.07036]

Coherent neutrino scattering

Combination of COHERENT constraints with other low- and high-energy electroweak precision tests

Assuming flavor generic Wilson coefficients the improvement is even more spectacular



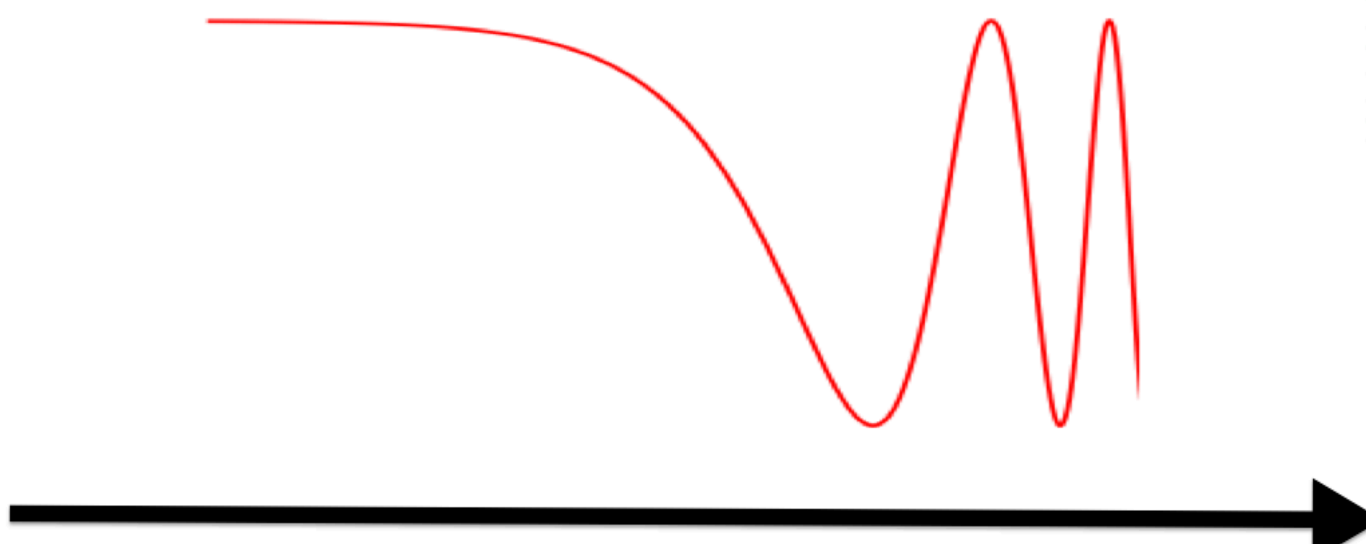


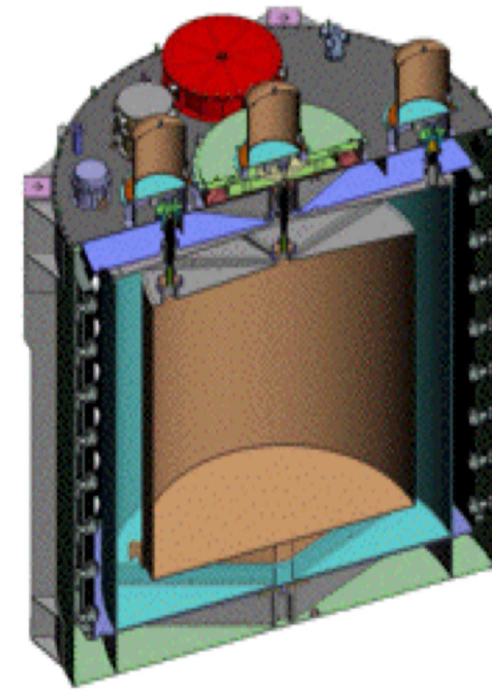
V. Breso-Pla et al
[arXiv:2301.07036]

Part 3

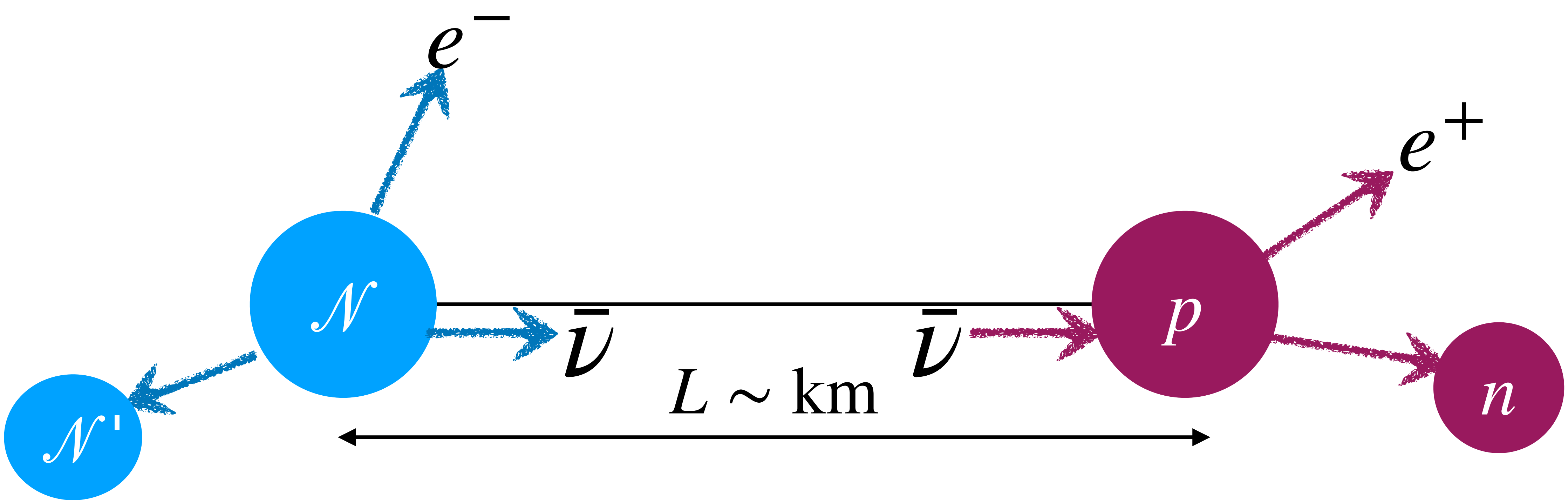
Constraints from reactor neutrino oscillations

$$\bar{\nu}_e \to \bar{\nu}_e$$





Reactor neutrino oscillations



$$d\bar{R}_{ee} = \sum_{\mathcal{N}} f_{\mathcal{N}} \frac{N_S N_T}{32\pi L^2 m_{\mathcal{N}} m_p} \sum_{k,l=1}^{3} e^{-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}} \left[d\Pi_P \mathcal{M}_{ek}^{P} \mathcal{M}_{el}^{P*}\right] \left[d\Pi_D \mathcal{M}_{ek}^{D} \mathcal{M}_{el}^{D*}\right]$$

Weighted sum over nuclei in reactor

$$\mathcal{M}_{ek}^{P} \equiv \mathcal{M}[\mathcal{N} \to \mathcal{N}' e^- \bar{\nu}_k]$$

$$\mathcal{M}_{ek}^{D} \equiv \mathcal{M}[\bar{\nu}_k p \to e^+ n]$$

Reactor neutrino oscillations

$$dR_{\alpha\beta} = \frac{N_S N_T}{32\pi L^2 m_S m_T} \sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}\right) d\Pi_P \mathcal{M}^P_{\alpha k} \bar{\mathcal{M}}^P_{\alpha l} d\Pi_D \mathcal{M}^D_{\beta k} \bar{\mathcal{M}}^D_{\beta l}$$

The rate above is already an observable in neutrino experiments, and this is what is used in practical analyses, but to compare to commonly used language we can define oscillation probability

$$\frac{dP_{\alpha\beta}}{dE_\nu} = \frac{\int \frac{dR_{\alpha\beta}}{dE_\nu}}{\frac{d\Phi_\alpha}{dE_\nu}\sigma_\beta}$$

Neutrino flux at the source — **Neutrino cross section at the target**

$$\frac{dP_{\alpha\beta}}{dE_\nu} = \frac{\sum_{k,l=1}^{3} \exp\left(-i\frac{L(m_k^2 - m_l^2)}{2E_\nu}\right) \int \frac{d\Pi_P}{dE_\nu} \mathcal{M}^P_{\alpha k} \bar{\mathcal{M}}^P_{\alpha l} \int d\Pi_D \mathcal{M}^D_{\beta k} \bar{\mathcal{M}}^D_{\beta l}}{\sum_{k,l=1}^{3} \int \frac{d\Pi_P}{dE_\nu} |\mathcal{M}^P_{\alpha k}|^2 \int d\Pi_D |\mathcal{M}^D_{\beta l}|^2}$$

Reactor neutrino oscillations

Leading order Ccarged current Lagrangian at low energy can be parametrized as

$$\mathscr{L}_{WEFT} \supset -\frac{2V_{ud}}{\mathrm{v}^2}\Bigg[\Big[1+\epsilon_L\Big]_{\alpha\beta}\bar{e}_\alpha\gamma_\mu P_L\nu_\beta\cdot\bar{u}_L\gamma^\mu d_L$$

$$+\Big[\epsilon_R\Big]_{\alpha\beta}\bar{e}_\alpha\gamma_\mu P_L\nu_\beta\cdot\bar{u}_R\gamma^\mu d_R$$

$$+\frac{1}{2}\bar{e}_\alpha P_L\nu_\beta\cdot\bar{u}\Big[\epsilon_S-\epsilon_P\gamma_5\Big]_{\alpha\beta}d$$

$$+\frac{1}{4}\Big[\epsilon_T\Big]_{\alpha\beta}\bar{e}_\alpha\sigma_{\mu\nu}P_L\nu_\beta\cdot\bar{u}_R\sigma^{\mu\nu}d_L\Bigg]+\mathrm{h.c.}$$

Matching to SMEFT

$$[\epsilon_L]_{\alpha\beta}=\frac{\mathrm{v}^2}{V_{ud}}\left(V_{ud}[C^{(3)}_{Hl}]_{\alpha\beta}+V_{jd}[C^{(3)}_{Hq}]_{1j}\delta_{\alpha\beta}-V_{jd}[C^{(3)}_{lq}]_{\alpha\beta1j}\right)$$

$$[\epsilon_R]_{\alpha\beta}=\frac{\mathrm{v}^2}{2V_{ud}}[C_{Hud}]_{11}\delta_{\alpha\beta}$$

$$[\epsilon_S]_{\alpha\beta}=-\frac{\mathrm{v}^2}{2V_{ud}}\left(V_{jd}[C^{(1)}_{lequ}]^*_{\beta\alpha j1}+[C_{ledq}]^*_{\beta\alpha11}\right)$$

$$[\epsilon_P]_{\alpha\beta}=-\frac{\mathrm{v}^2}{2V_{ud}}\left(V_{jd}[C^{(1)}_{lequ}]^*_{\beta\alpha j1}-[C_{ledq}]^*_{\beta\alpha11}\right)$$

$$[\epsilon_T]_{\alpha\beta}=-\frac{2\mathrm{v}^2}{V_{ud}}V_{jd}[C^{(3)}_{lequ}]^*_{\beta\alpha j1}$$

Reactor neutrino oscillations

AA, M. Gonzalez-Alonso, Z. Tabrizi
[arXiv:1901.04553]

In the limit $\frac{\Delta m_{21}^2 L}{E_\nu} \ll 1$, the survival probability takes the form

$$P_{\bar\nu_e\to\bar\nu_e} = 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\tilde\theta_{13} - \alpha_D \frac{m_e}{E_\nu - \Delta} - \alpha_P \frac{m_e}{f_T(E_\nu)}\right)$$
$$+\sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde\theta_{13})\left(\beta_D \frac{m_e}{E_\nu - \Delta} - \beta_P \frac{m_e}{f_T(E_\nu)}\right) + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(\Delta m_{21}^2)$$

Approximately known function depending on distribution of radioactive nuclei in reactor

$$\alpha_D = \frac{g_S}{3g_A^2+1}\mathrm{Re}\,[S] - \frac{3g_A g_T}{3g_A^2+1}\mathrm{Re}\,[T] \qquad \alpha_P = \frac{g_T}{g_A}\mathrm{Re}\,[T] \qquad \tilde\theta_{13} = \theta_{13} + \mathrm{Re}[L]$$

$$\beta_D = \frac{g_S}{3g_A^2+1}\mathrm{Im}\,[S] - \frac{3g_A g_T}{3g_A^2+1}\mathrm{Im}\,[T], \qquad \beta_P = \frac{g_T}{g_A}\mathrm{Im}\,[T] \qquad [X] \equiv e^{i\delta_{\mathrm{CP}}}\left(s_{23}[\epsilon_X]_{e\mu} + c_{23}[\epsilon_X]_{e\tau}\right)$$

Short baseline reactor neutrino oscillations sensitive to 5 distinct linear combinations of dimension-6 SMEFT operators

Effects of SM-like V-A interactions parametrized by ϵ_L are absorbed into mixing angle, thus they are not observable in reactor oscillations alone!

Reactor neutrino oscillations

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\tilde{\theta}_{13} - \alpha_D\frac{m_e}{E_\nu - \Delta} - \alpha_P\frac{m_e}{f_T(E_\nu)}\right)$$
$$+\sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde{\theta}_{13})\left(\beta_D\frac{m_e}{E_\nu - \Delta} - \beta_P\frac{m_e}{f_T(E_\nu)}\right) + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(\Delta m_{21}^2)$$

The real parts of scalar and tensor parameters lead to "energy-dependent mixing angle":

$$\alpha_D = \frac{g_S}{3g_A^2+1}\mathrm{Re}\,[S] - \frac{3g_A g_T}{3g_A^2+1}\mathrm{Re}\,[T]$$

$$\beta_D = \frac{g_S}{3g_A^2+1}\mathrm{Im}\,[S] - \frac{3g_A g_T}{3g_A^2+1}\mathrm{Im}\,[T], \qquad [X] \equiv e^{i\delta_{\mathrm{CP}}}\left(s_{23}[\epsilon_X]_{e\mu} + c_{23}[\epsilon_X]_{e\tau}\right)$$

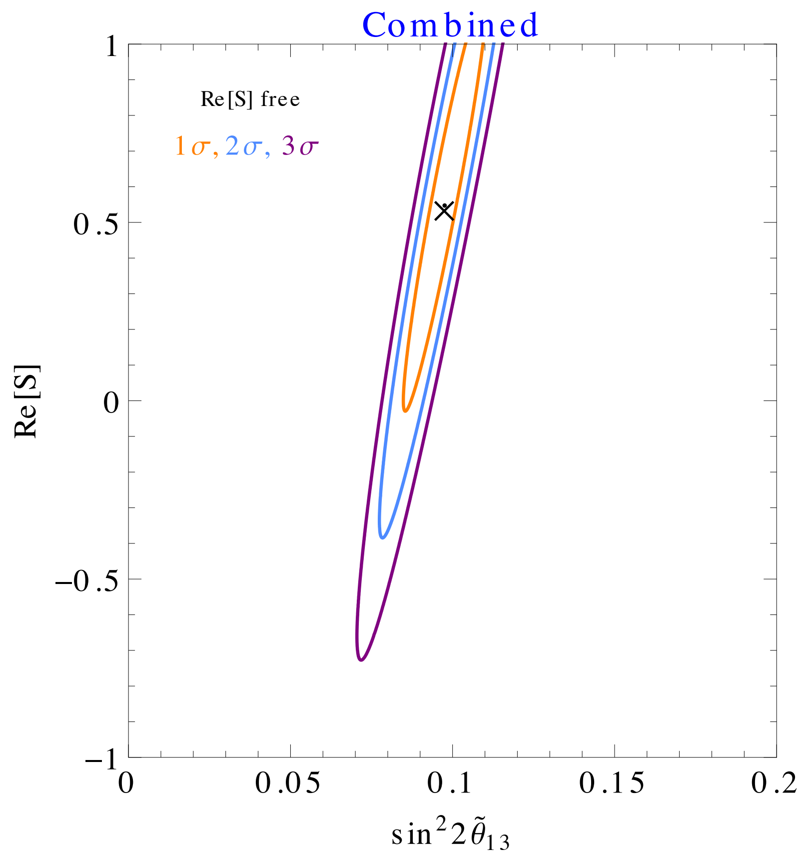
The imaginary parts of scalar and tensor parameters lead to qualitatively distinct oscillation pattern

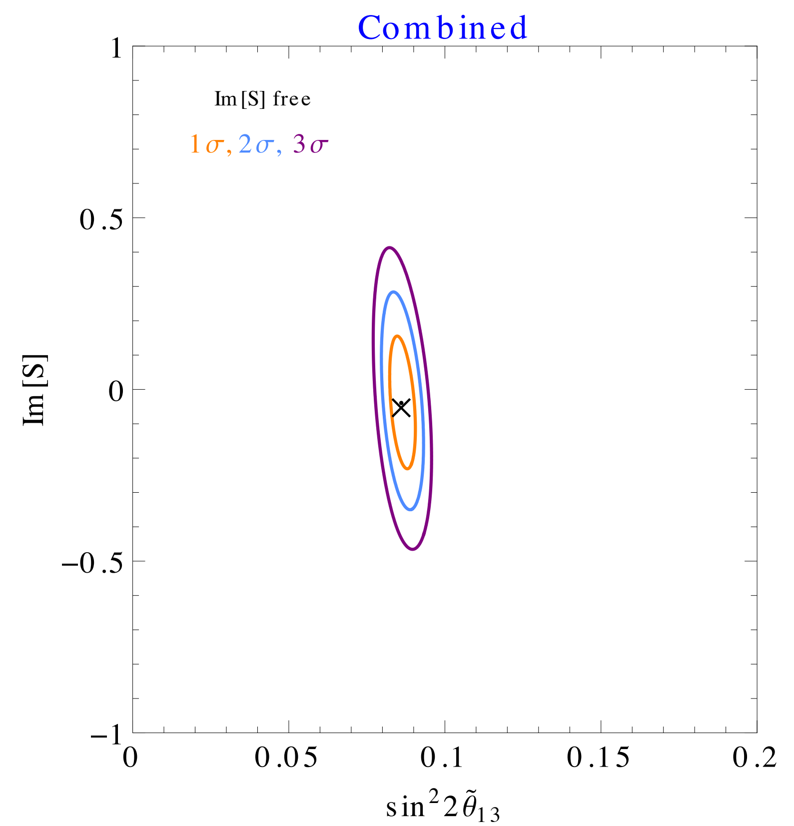
A possible handle to constrain these effects, as neutrino experiments quote results in energy bins

Reactor neutrino oscillations

Combined constraints using RENO and Daya Bay data

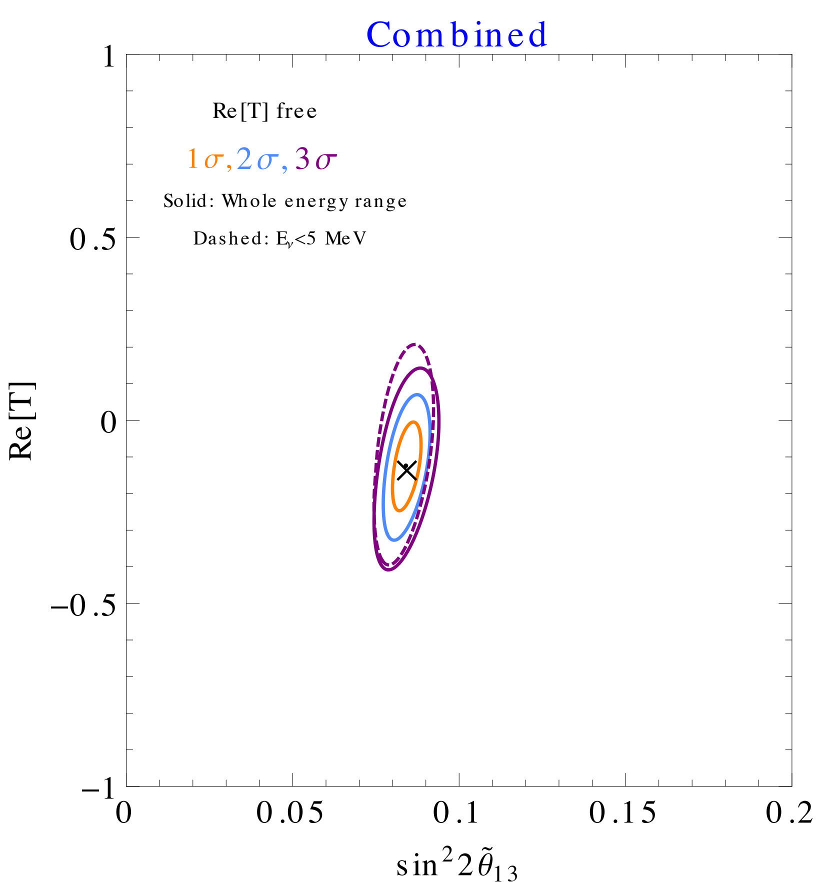
AA, M. Gonzalez-Alonso, Z. Tabrizi
[arXiv:1901.04553]

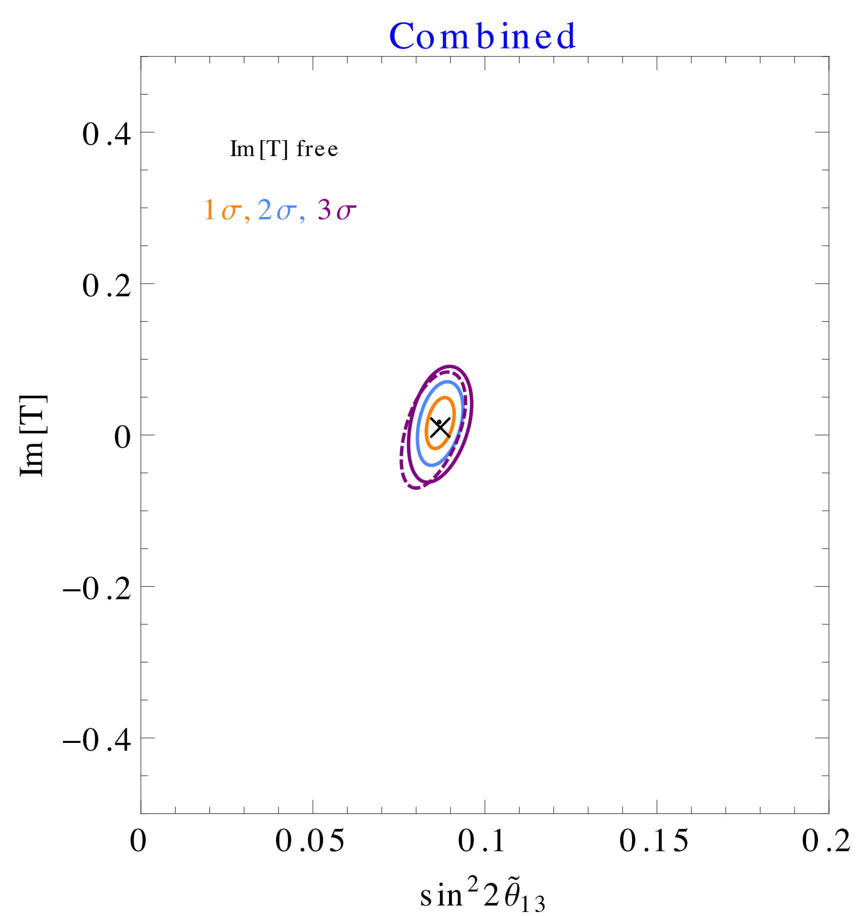




$$-[\epsilon_S]_{\alpha\beta}\frac{2V_{ud}}{v^2}\frac{1}{2}\bar{e}_\alpha P_L \nu_\beta \cdot \bar{u} d$$

Better constraints on real than imaginary parts



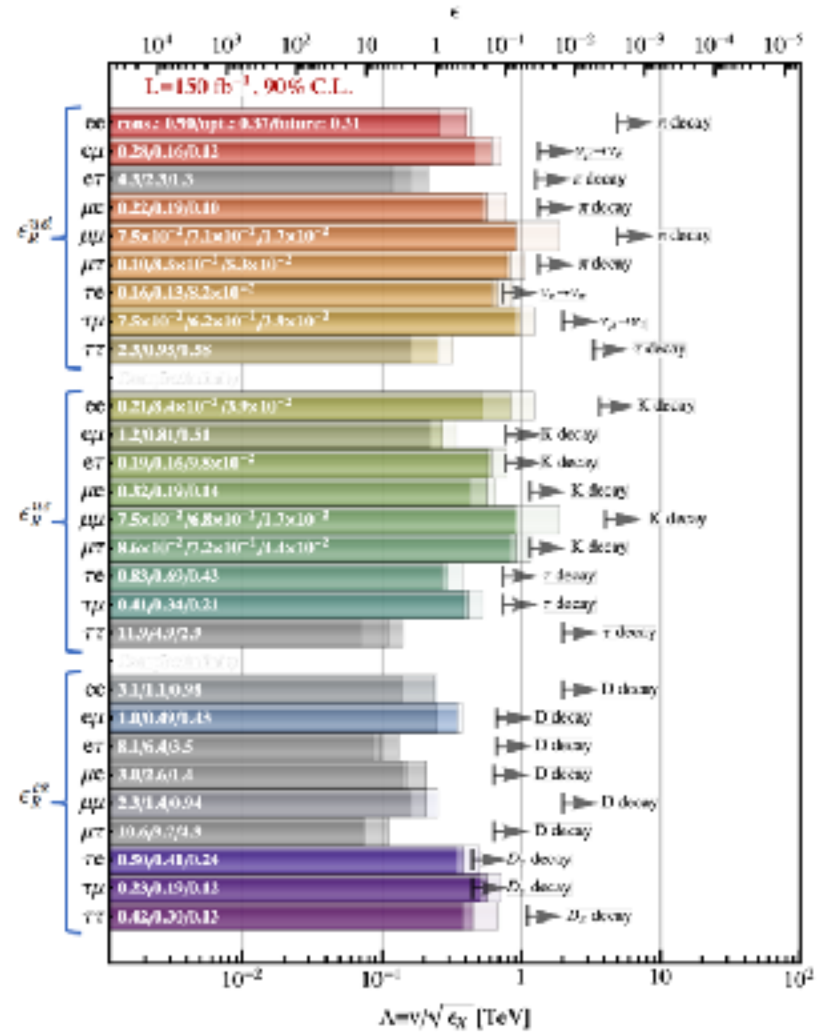


Somewhat better constraint on tensor than scalar

$$-\left[\epsilon_T\right]_{\alpha\beta}\frac{2V_{ud}}{v^2}\frac{1}{4}\,\bar{e}_\alpha \sigma_{\mu\nu} P_L \nu_\beta \cdot \bar{u}_R \sigma^{\mu\nu} d_L$$

See also the analysis by Daya Bay [arXiv:2401.02901]

See also

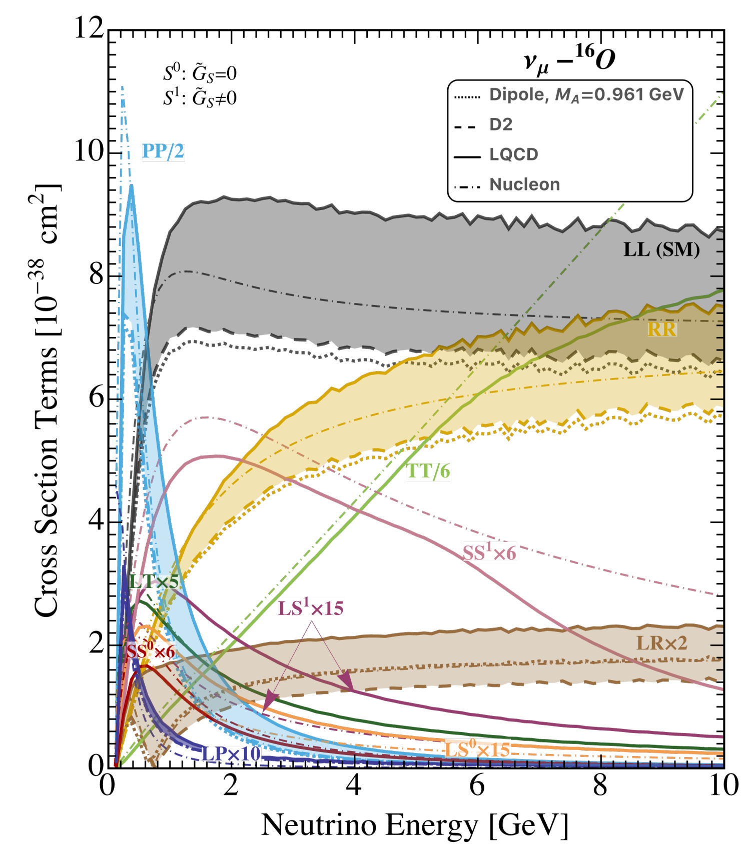


EFT Faserν sensitivity study

AA, M. Gonzalez-Alonso, J. Kopp, Y. Soreq, Z. Tabrizi
[arXiv:1901.04553]

Discussion of neutrino detection in the quasi-elastic regime

J. Kopp, N. Rocco, Z. Tabrizi
[arXiv::2401.07902]

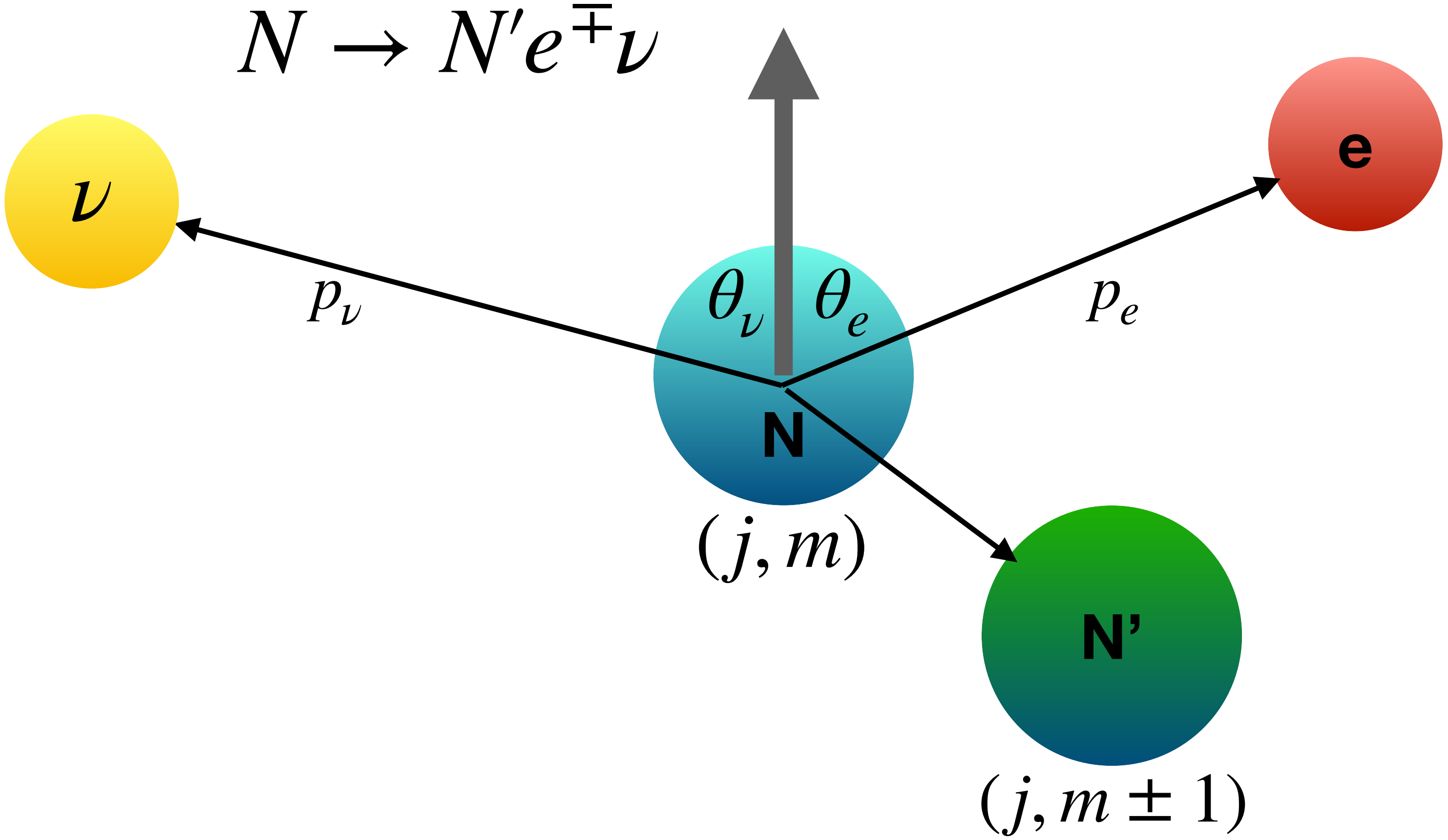


Part 3

Constraints from CP violation in nuclear beta decay

Observables in beta decay

$$N \to N' e^{\mp} \nu$$



Electron energy/momentum

$$E_e = \sqrt{p_e^2 + m_e^2}$$

Neutrino energy

$$E_\nu = p_\nu \approx m_N - m_{N'} - E_e$$

Information about the Wilson coefficients can be accessed by measuring (differential) decay width:

Control lifetime and beta spectrum ($F(E_e)$, b)

Routinely measured correlations (a, A, B)

Main focus here (D)

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = F(E_e)\left\{ 1 + b\frac{m_e}{E_e} + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu}{E_e E_\nu} + A\frac{\langle \boldsymbol{J} \rangle \cdot \boldsymbol{p}_e}{J E_e} + B\frac{\langle \boldsymbol{J} \rangle \cdot \boldsymbol{p}_\nu}{J E_\nu} + c\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu - 3(\boldsymbol{p}_e \cdot \boldsymbol{j})(\boldsymbol{p}_\nu \cdot \boldsymbol{j})}{3 E_e E_\nu}\left[\frac{J(J+1) - 3(\langle \boldsymbol{J} \rangle \cdot \boldsymbol{j})^2}{J(2J-1)}\right] + {\color{red}D}\frac{\langle \boldsymbol{J} \rangle \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu)}{J E_e E_\nu} \right\}$$

No-one talks about it (c)

D parameter

Jackson Treiman Wyld (1957)

$$\mathscr{L}^{(0)} = -(\psi_p^\dagger \psi_n)\left[C_V^+ \bar{e}\bar{\sigma}^0\nu + C_V^- e^c\sigma^0\bar{\nu}^c + C_S^+ e^c\nu + C_S^- \bar{e}\bar{\nu}^c\right]$$

$$+ \sum_{k=1}^{3}(\psi_p^\dagger \sigma^k \psi_n)\left[C_A^+ \bar{e}\bar{\sigma}^k\nu + C_A^+ e^c\sigma^k\bar{\nu}^c + C_T^+ e^c\sigma^0\bar{\sigma}^k\nu + C_T^- \bar{e}\bar{\sigma}^k\bar{\sigma}^0\bar{\nu}^\nu\right]$$

For same spin (J'=J) mixed allowed beta transitions:

$$D = -2r\sqrt{\frac{J}{J+1}}\frac{\mathrm{Im}\left\{C_V^+\bar{C}_A^+ - C_S^+\bar{C}_T^+ + C_V^-\bar{C}_A^- - C_S^-\bar{C}_T^-\right\}}{|C_V^+|^2 + |C_S^+|^2 + |C_V^-|^2 + |C_S^-|^2 + r^2\left[|C_A^+|^2 + |C_T^+|^2 + |C_A^-|^2 + |C_T^-|^2\right]}$$

Ratio of GT and Fermi matrix elements extracted from global fits

For D parameter to be non-zero:

- Beta decay has to neither pure Fermi nor pure GT

$$r \approx -\rho/g_A$$

- At least two distinct Wilson coefficients have to be non-zero

- There has to be a relative phase difference between these two parameters

So-called mixing parameter

D parameter

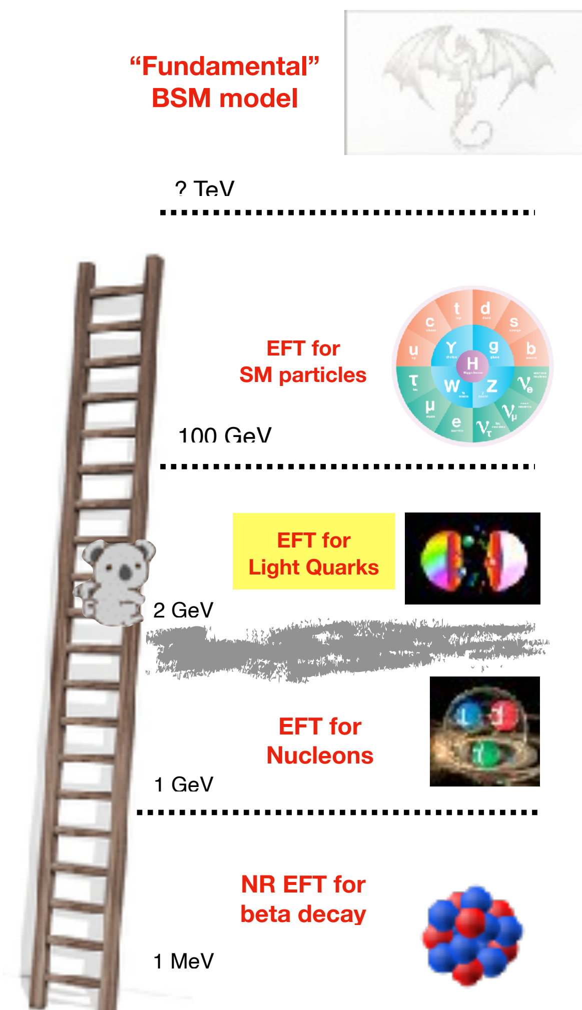
Translation to the quark-level Wilson coefficients below the electroweak scale:

$$
\begin{aligned}
\mathscr{L} \supset -\frac{2V_{ud}}{v^2}\Big\{ & (1+\epsilon_L)\ \bar{e}\bar{\sigma}_\mu \nu \cdot \bar{u}\bar{\sigma}^\mu d && + \ \tilde{\epsilon}_L\, e^c \sigma_\mu \bar{\nu}^c \cdot \bar{u}\bar{\sigma}^\mu d \\
& + \epsilon_R\, \bar{e}\bar{\sigma}_\mu \nu \cdot u^c \sigma^\mu \bar{d}^c && + \ \tilde{\epsilon}_R\, e^c \sigma_\mu \bar{\nu}^c u^c \sigma^\mu \bar{d}^c \\
& + \epsilon_T \frac{1}{4} e^c \sigma_{\mu\nu} \nu \cdot u^c \sigma^{\mu\nu} d && + \ \tilde{\epsilon}_T \frac{1}{4} \bar{e}^c \bar{\sigma}_{\mu\nu} \bar{\nu}^c \cdot \bar{u}\bar{\sigma}^{\mu\nu} \bar{d}^c \\
& + \epsilon_S \frac{1}{2} e^c \nu \cdot (u^c d + \bar{u}\bar{d}^c) && + \ \tilde{\epsilon}_S \frac{1}{2} \bar{e}\bar{\nu}^c \cdot (u^c d + \bar{u}\bar{d}^c) \\
& + \epsilon_P \frac{1}{2} e^c \nu \cdot (u^c d - \bar{u}\bar{d}^c) && - \ \tilde{\epsilon}_P \frac{1}{2} \bar{e}\bar{\nu}^c \cdot (u^c d - \bar{u}\bar{d}^c) \Big\} + \mathrm{h.c.}
\end{aligned}
$$

$$
D = \frac{4 r g_V g_A}{g_V^2 + r^2 g_A^2}\sqrt{\frac{J}{J+1}}\,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + \frac{g_S g_T}{2 g_V g_A}(\epsilon_S \epsilon_T^* + \tilde{\epsilon}_S \tilde{\epsilon}_T^*) - \tilde{\epsilon}_R \tilde{\epsilon}_L^*\right]
$$

At the linear level in Wilson coefficients, D parameter measures the imaginary part of non-standard right-handed currents involving the left-handed neutrino

At the quadratic level, sensitivity to imaginary parts of scalar and tensor current and to interactions of right-handed neutrino

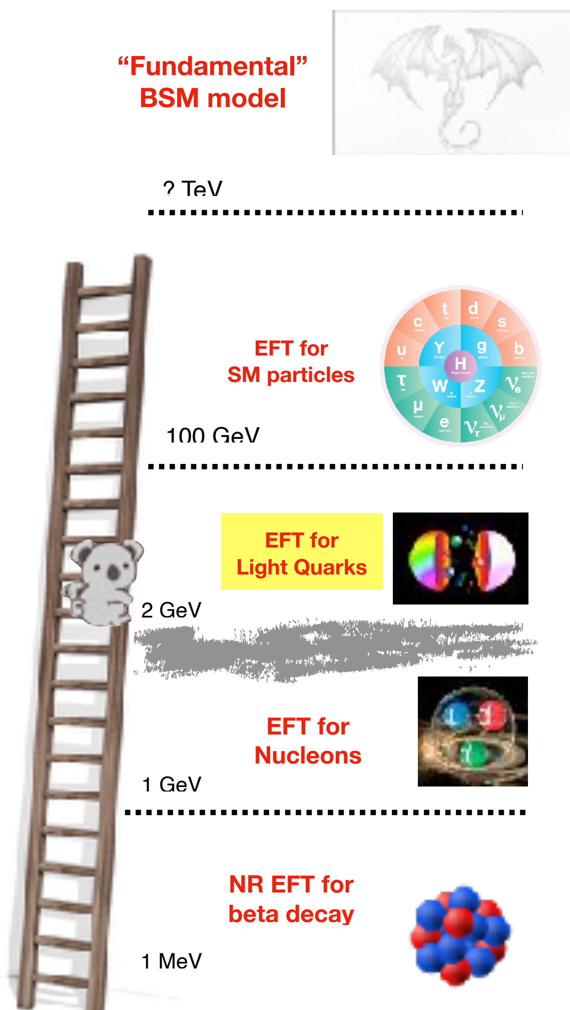


D parameter

Translation to the quark-level Wilson coefficients:

$$\mathscr{L} \supset -\frac{2V_{ud}}{v^2}\Big\{ (1+\epsilon_L)\ \bar{e}\bar{\sigma}_\mu\nu \cdot \bar{u}\bar{\sigma}^\mu d \quad + \ \tilde{\epsilon}_L\, e^c\sigma_\mu\bar{\nu}^c \cdot \bar{u}\bar{\sigma}^\mu d$$
$$+\epsilon_R\, \bar{e}\bar{\sigma}_\mu\nu \cdot u^c\sigma^\mu\bar{d}^c \quad + \ \tilde{\epsilon}_R\, e^c\sigma_\mu\bar{\nu}^c u^c\sigma^\mu\bar{d}^c$$
$$+\epsilon_T\frac{1}{4}e^c\sigma_{\mu\nu}\nu \cdot u^c\sigma^{\mu\nu}d \quad + \ \tilde{\epsilon}_T\frac{1}{4}\bar{e}^c\bar{\sigma}_{\mu\nu}\bar{\nu}^c \cdot \bar{u}\bar{\sigma}^{\mu\nu}\bar{d}^c$$
$$+\epsilon_S\frac{1}{2}e^c\nu \cdot (u^c d + \bar{u}\bar{d}^c) \quad + \ \tilde{\epsilon}_S\frac{1}{2}\bar{e}\bar{\nu}^c \cdot (u^c d + \bar{u}\bar{d}^c)$$
$$+\epsilon_P\frac{1}{2}e^c\nu \cdot (u^c d - \bar{u}\bar{d}^c) \quad - \ \tilde{\epsilon}_P\frac{1}{2}\bar{e}\bar{\nu}^c \cdot (u^c d - \bar{u}\bar{d}^c)\Big\} + \mathrm{h.c.}$$

$$D \approx \kappa_D\, \mathrm{Im}\big[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\big] \qquad \kappa_D \equiv \frac{4 r g_V g_A}{g_V^2 + r^2 g_A^2}\sqrt{\frac{J}{J+1}}$$



Parent	J	r	κ_D	D_{exp}	$\Delta D_{\mathrm{future}}$
n	$1/2$	$\sqrt{3}$	0.88	$-1.2(2.0)\times 10^{-4}$ [12]	-
^{19}Ne	$1/2$	-1.26	-1.04	$0.0001(6)$	-
^{23}Mg	$3/2$	-0.44	-1.30	-	3.8×10^{-5} [13]
^{39}Ca	$3/2$	0.52	1.42	-	$< 10^{-4}$ [13]

D parameter

Translation to Wilson coefficients of EFT above electroweak scale

$$
\begin{aligned}
\mathcal{L}_{\nu\mathrm{SMEFT}} \supset\ & iC_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar{d}^c) && + iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar{\nu}^c) \\
& + C^{(3)}_{lequ} (\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) && + C^{(3)}_{l\nu qd} (\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c) \\
& + C^{(1)}_{lequ} (\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) && + C^{(1)}_{l\nu qd} (\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c) \\
& + C_{ledq} (\bar{l}\bar{e}^c)(d^c q) && + C_{l\nu uq} (\bar{l}\bar{\nu}^c)(u^c q) \\
& && + C_{e\nu ud} (e^c \sigma^\mu \bar{\nu}^c)(u^c \sigma_\mu \bar{d}^c) \\
& + \mathrm{hc}
\end{aligned}
$$

$$
D \approx \kappa_D \,\mathrm{Im}\left[\epsilon_R (1 + \epsilon_L^*) + 0.4(\epsilon_S \epsilon_T^* + \tilde{\epsilon}_S \tilde{\epsilon}_T^*) - \tilde{\epsilon}_R \tilde{\epsilon}_L^*\right]
$$

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}} C_{\phi ud}$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}} \left(C^{(1)*}_{lequ} + V_{ud} c^*_{ledq}\right)$$

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}} \left(C^{(1)*}_{lequ} - V_{ud} C^*_{ledq}\right)$$

$$\epsilon_T = -\frac{2\mathrm{v}^2}{V_{ud}} C^{(3)*}_{lequ}$$

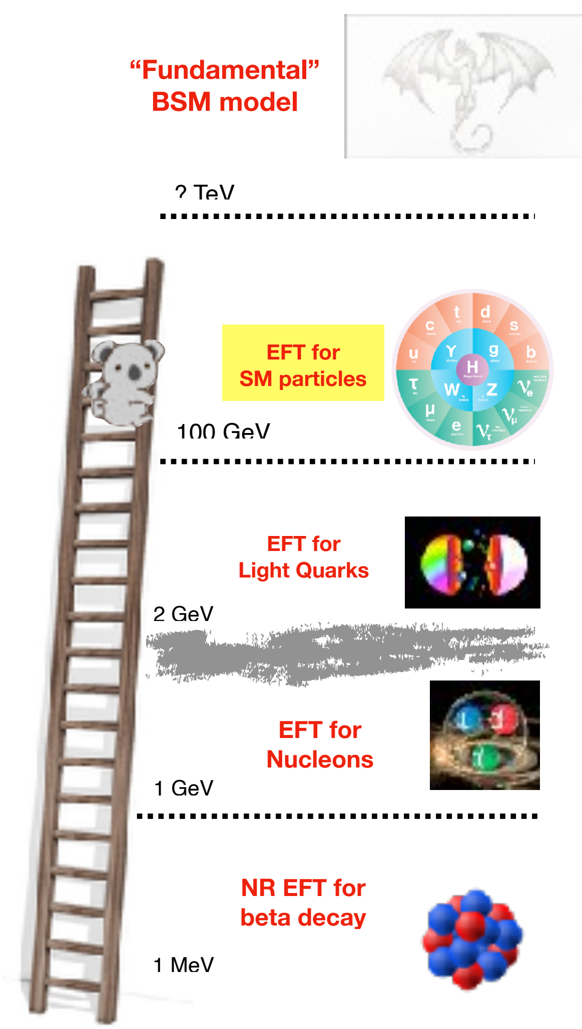
$$\tilde{\epsilon}_L = -\frac{\mathrm{v}^2}{2} C_{\phi e\nu}$$

$$\tilde{\epsilon}_R = -\frac{\mathrm{v}^2}{2V_{ud}} C_{e\nu ud}$$

$$\tilde{\epsilon}_S = \frac{\mathrm{v}^2}{2V_{ud}} \left[C^{(1)}_{l\nu qd} V_{ud} - C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_P = -\frac{\mathrm{v}^2}{2V_{ud}} \left[C^{(1)}_{l\nu qd} V_{ud} + C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$



D parameter scenarios

$$D \approx \kappa_D \,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde\epsilon_S\tilde\epsilon_T^*) - \tilde\epsilon_R\tilde\epsilon_L^*\right]$$

Scenario #1 → $\epsilon_R(1+\epsilon_L^*)$

Scenario #2 → $\epsilon_S\epsilon_T^*$

Scenario #3 → $\tilde\epsilon_S\tilde\epsilon_T^*$

Scenario #4 → $\tilde\epsilon_R\tilde\epsilon_L^*$

Scenario	νWEFT	νSMEFT	max $\lvert D\rvert$
I	ϵ_R	$HD_\mu H u^c\sigma^\mu\bar d^c$ $[(\bar l H\bar\sigma_\mu H l)(u^c\sigma^\mu\bar d^c)]$	?
II	$\epsilon_S,\ \epsilon_T$	$(\bar l\bar\sigma_{\mu\nu}\bar e^c)(\bar q\bar\sigma^{\mu\nu}\bar u^c)$, $(\bar l\bar e^c)(\bar q\bar u^c)$, $(\bar l\bar e^c)(d^c q)$	
III	$\tilde\epsilon_S,\ \tilde\epsilon_T$	$(\bar l\bar\sigma^{\mu\nu}\bar\nu^c)(\bar q\bar\sigma_{\mu\nu}\bar d^c)$, $(\bar l\bar\nu^c)(\bar q\bar d^c)$, $(\bar l\bar\nu^c)(u^c q)$	
IV	$\tilde\epsilon_L,\ \tilde\epsilon_R$	$H^\dagger D_\mu H^\dagger e^c\sigma^\mu\bar\nu^c$ $[e^c\sigma^\mu\bar\nu^c\bar q H^\dagger\sigma_\mu H^\dagger q]$, $(e^c\sigma^\mu\bar\nu^c)(u^c\sigma_\mu\bar d^c)$	

D parameter scenario #1

$$D \approx \kappa_D \,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\right]$$

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}} C_{\phi ud}$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C_{lequ}^{(1)*} + V_{ud} c_{ledq}^*\right)$$

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C_{lequ}^{(1)*} - V_{ud} C_{ledq}^*\right)$$

$$\epsilon_T = -\frac{2\mathrm{v}^2}{V_{ud}} C_{lequ}^{(3)*}$$

$$\begin{aligned}\mathcal{L}_{\rm EFT} \supset\; & iC_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar{d}^c) & & +iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar{\nu}^c) \\ & + C_{lequ}^{(3)} (\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) & & + C_{l\nu qd}^{(3)} (\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c) \\ & + C_{lequ}^{(1)} (\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) & & + C_{l\nu qd}^{(1)} (\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c) \\ & + C_{ledq} (\bar{l}\bar{e}^c)(d^c q) & & + C_{l\nu uq} (\bar{l}\bar{\nu}^c)(u^c q) \\ & & & + C_{e\nu ud} (e^c \sigma^\mu \bar{\nu}^c)(u^c \sigma_\mu \bar{d}^c) \\ & + \mathrm{hc} & & \end{aligned}$$

One can generate imaginary right-handed currents from a dimension-6 or a dimension-8 operator

D parameter scenario #1a

$$D \approx \kappa_D \,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S \epsilon_T^* + \tilde\epsilon_S \tilde\epsilon_T^*) - \tilde\epsilon_R \tilde\epsilon_L^*\right]$$

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}} C_{\phi ud}$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C^{(1)*}_{lequ} + V_{ud} c^*_{ledq}\right)$$

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C^{(1)*}_{lequ} - V_{ud} C^*_{ledq}\right)$$

$$\epsilon_T = -\frac{2\mathrm{v}^2}{V_{ud}} C^{(3)*}_{lequ}$$

$$\mathscr{L}_{\mathrm{EFT}} \supset i C_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar d^c) + C^{(3)}_{lequ}(\bar l \bar\sigma_{\mu\nu} \bar e^c)(\bar q \bar\sigma^{\mu\nu} \bar u^c) + C^{(1)}_{lequ}(\bar l \bar e^c)(\bar q \bar u^c) + C_{ledq}(\bar l \bar e^c)(d^c q)$$

$$+ i C_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar\nu^c) + C^{(3)}_{l\nu qd}(\bar l \bar\sigma^{\mu\nu} \bar\nu^c)(\bar q \bar\sigma_{\mu\nu} \bar d^c) + C^{(1)}_{l\nu qd}(\bar l \bar\nu^c)(\bar q \bar d^c) + C_{l\nu uq}(\bar l \bar\nu^c)(u^c q) + C_{e\nu ud}(e^c \sigma^\mu \bar\nu^c)(u^c \sigma_\mu \bar d^c)$$

$$+\mathrm{hc}$$

Dimension-6 is naively a better option, because then $D \sim \frac{\mathrm{v}^2}{\Lambda^2}$

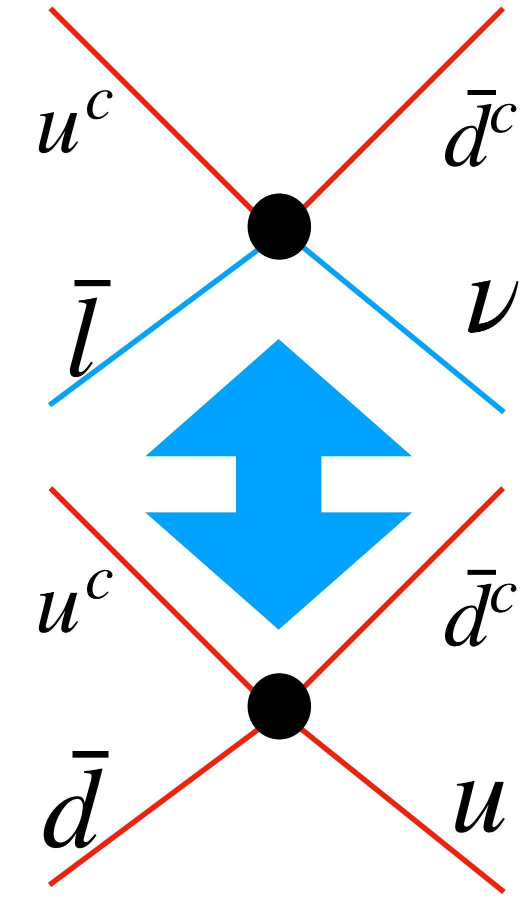
where v=246 GeV is the electroweak scale, and Λ is the mass scale of new BSM particles

Moreover, the Wilson coefficients $C_{\phi ud}$ is generated by many motivated BSM models, for example by the left-right symmetric models

However, there are strong model-independent constraints from EDMs...

D parameter scenario #1a

$$\mathscr{L}_{\nu\text{SMEFT}} \supset \frac{g_L}{\sqrt{2}} W^+_\mu \left[\bar{\nu}\bar{\sigma}^\mu e + V_{ud}\bar{u}\bar{\sigma}^\mu d + \frac{\text{v}^2}{2} C_{\phi ud} u^c \sigma^\mu \bar{d}^c \right]$$



Integrating out the W boson

$$\mathscr{L}_{\nu\text{WEFT}} \supset -C_{\phi ud}(\bar{e}\bar{\sigma}_\mu \nu)(\bar{u}^c \sigma^\mu \bar{d}^c) - V_{ud} C_{\phi ud}(\bar{d}\bar{\sigma}_\mu u)(u^c \sigma^\mu \bar{d}^c) + \text{h.c.}$$

Contributes to D **Contributes to EDM**

$C_{\phi ud}$ **contributes not only to the D parameter, but also to a 4-quark operator contributing to nuclear EDM, with both contribution being governed by the same parameter**

EDM constraints dominated by 199Hg

$$\text{v}^2 |\text{Im}[C_{\phi ud}]| \lesssim 3 \times 10^{-6}$$

arXiv:2012.02799

It follows that assuming absence of fine-tuning

$$|D| \approx \frac{|\kappa_D|}{2} \text{v}^2 |\text{Im}[C_{\phi ud}]| \lesssim 2 \times 10^{-6}$$

using d_n from Alioli et al arXiv:1703.04751

if only neutron EDM contraints used

$$\text{v}^2 |\text{Im}C_{\phi ud}| \lesssim 1 \times 10^{-5}$$

$$|D| \lesssim 5 \times 10^{-6}$$

See Ramsey-Musolf & Vasquez [arXiv:2012.02799] for a more general discussion allowing fine-tuning EDM against θ_{QCD}

D parameter scenario #1b

$$D \approx \kappa_D \,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\right]$$

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}}C_{\phi ud} + \frac{\mathrm{v}^4}{4V_{ud}}C_8$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C^{(1)*}_{lequ} + V_{ud}c^*_{ledq}\right)$$

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C^{(1)*}_{lequ} - V_{ud}C^*_{ledq}\right)$$

$$\epsilon_T = -\frac{2\mathrm{v}^2}{V_{ud}}C^{(3)*}_{lequ}$$

$$\begin{aligned}\mathscr{L}_{\mathrm{EFT}} \supset\ & iC_{\phi ud}HD_\mu H(u^c\sigma^\mu\bar{d}^c) && +iC_{\phi e\nu}H^\dagger D_\mu H^\dagger(e^c\sigma^\mu\bar{\nu}^c)\\ & +C^{(3)}_{lequ}(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) && +C^{(3)}_{l\nu qd}(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)\\ & +C^{(1)}_{lequ}(\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) && +C^{(1)}_{l\nu qd}(\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)\\ & +C_{ledq}(\bar{l}\bar{e}^c)(d^cq) && +C_{l\nu uq}(\bar{l}\bar{\nu}^c)(u^cq)\\ & +C_8(\bar{l}H\bar{\sigma}_\mu Hl)(u^c\sigma^\mu\bar{d}^c) && +C_{e\nu ud}(e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu\bar{d}^c)\\ & +\mathrm{hc} && \end{aligned}$$

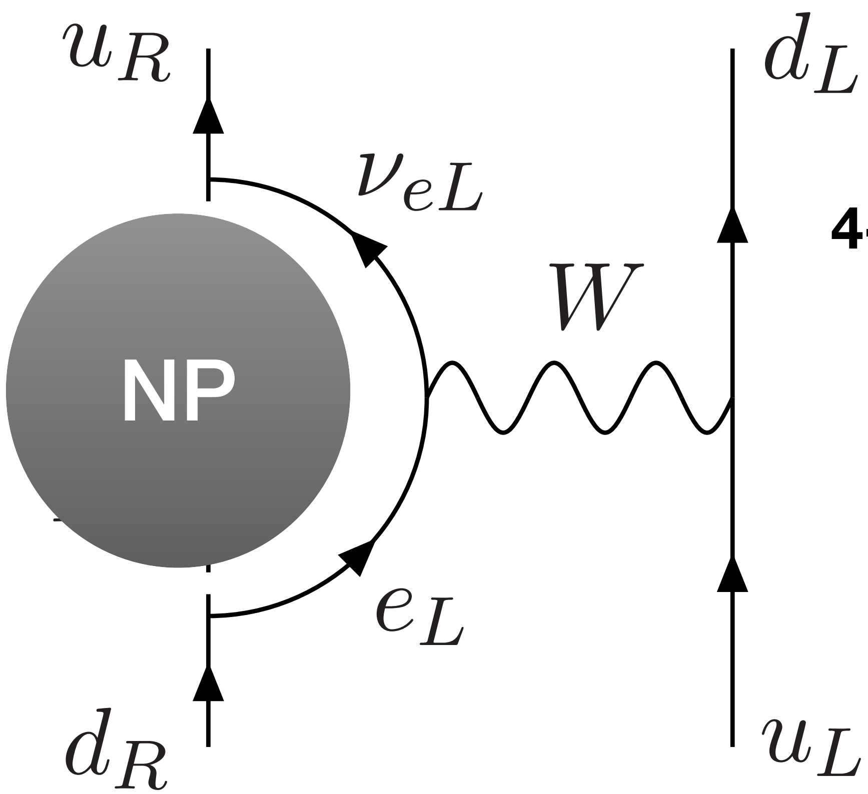
Generating D parameter via a dimension-8 operator means that D is more suppressed: $D \sim \frac{\mathrm{v}^4}{\Lambda^4}$

where v=246 GeV is the electroweak scale, and Λ is the mass scale of new BSM particles
This dimension-8 operator can be generated at tree level in certain leptoquark models

Ng Tulin
arXiv:1111.0649

Constraints from EDMs are now model dependent...

D parameter scenario #1b



As soon as 4-fermion vertex leading to non-zero ϵ_R appears, 4-quark operators leading to EDM is generated at 1 loop in EFT although its coefficient is not calculable in EFT

$$\mathscr{L}_{\nu\mathrm{WEFT}} \supset -C_{1LR}(\bar{d}\bar{\sigma}_\mu u)(u^c\sigma^\mu \bar{d}^c) + \mathrm{h.c.}$$

$$C_{1LR} \sim \frac{C_8\Lambda^2}{16\pi^2} \Rightarrow \mathrm{v}^2\Lambda^2\mathrm{Im}C_8 \lesssim 3\times 10^{-4}$$

$$|D| \sim \frac{\mathrm{v}^4\mathrm{Im}C_8}{4} \lesssim 10^{-4}\frac{\mathrm{v}^2}{\Lambda^2}$$

In the scenario 1b the D parameter can be large only when new physics is at the EW scale, which is difficult to achieve in realistic models.

As soon as new physics is at 3 TeV, we are back to the severe constraint $|D| \lesssim 10^{-6}$

Mind that these are just rough estimates, a quantitative limit can be obtained only in concrete UV models where the quadratic divergence is resolved

D parameter scenario 1c

$$D \approx \kappa_D \,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\right]$$

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}} C_{\phi ud} + \frac{\mathrm{v}^4}{4V_{ud}} C_8$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C_{lequ}^{(1)*} + V_{ud} c_{ledq}^*\right)$$

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C_{lequ}^{(1)*} - V_{ud} C_{ledq}^*\right)$$

$$\epsilon_T = -\frac{2\mathrm{v}^2}{V_{ud}} C_{lequ}^{(3)*}$$

$$\begin{aligned}\mathscr{L}_{\mathrm{EFT}} \supset\ & iC_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar{d}^c) && + iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar{\nu}^c) \\ & + C_{lequ}^{(3)} (\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) && + C_{l\nu qd}^{(3)} (\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c) \\ & + C_{lequ}^{(1)} (\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) && + C_{l\nu qd}^{(1)} (\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c) \\ & + C_{ledq} (\bar{l}\bar{e}^c)(d^c q) && + C_{l\nu uq} (\bar{l}\bar{\nu}^c)(u^c q) \\ & + C_8 (\bar{l} H \bar{\sigma}_\mu H l)(u^c \sigma^\mu \bar{d}^c) && + C_{e\nu ud} (e^c \sigma^\mu \bar{\nu}^c)(u^c \sigma_\mu \bar{d}^c) \\ & + \mathrm{hc}\end{aligned}$$

One more possible option is that operators contributing to ϵ_R are real (CP conserving), and the imaginary part is contained in ϵ_L.
Note that the real part ϵ_R can be at percent level, as constraints are relatively weak

[arXiv:2010.13797] with Martin Gonzalez-Alonso, Oscar Naviliat-Cuncic

D parameter scenario 1c

$$D \approx \kappa_D \operatorname{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\right]$$

One more possible option is that operators contributing to ϵ_R are real (CP conserving), and the imaginary part is contained in ϵ_L.

This is not a very attractive scenario for BSM, because dimension-6 operators lead to a real ϵ_L, thus D would be at least of order $\frac{v^6}{\Lambda^6}$

However, ϵ_L effectively acquires a complex part due to SM loop effect, because of a photon going on-shell in the loop
Thus, in the scenario 1c the D parameter may be a sensitive probe of CP conserving new physics contribution to $\epsilon_R \sim \frac{v^2}{\Lambda^2}$, as long as the SM contribution can be reliably calculated

D parameter scenario #2

$$D \approx \kappa_D \, \mathrm{Im}\big[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\big]$$

$$\epsilon_R = \frac{v^2}{2V_{ud}} C_{\phi ud}$$

$$\epsilon_S = -\frac{v^2}{2V_{ud}}\left(C_{lequ}^{(1)*} + V_{ud} c_{ledq}^*\right)$$

$$\epsilon_P = -\frac{v^2}{2V_{ud}}\left(C_{lequ}^{(1)*} - V_{ud} C_{ledq}^*\right)$$

$$\epsilon_T = -\frac{2v^2}{V_{ud}} C_{lequ}^{(3)*}$$

$$\mathcal{L}_{\rm EFT} \supset iC_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar{d}^c) + C_{lequ}^{(3)} (\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) + C_{lequ}^{(1)} (\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) + C_{ledq} (\bar{l}\bar{e}^c)(d^c q) + \mathrm{hc}$$

$$+ iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar{\nu}^c) + C_{l\nu qd}^{(3)} (\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c) + C_{l\nu qd}^{(1)} (\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c) + C_{l\nu uq} (\bar{l}\bar{\nu}^c)(u^c q) + C_{e\nu ud} (e^c \sigma^\mu \bar{\nu}^c)(u^c \sigma_\mu \bar{d}^c)$$

This scenario is doomed from the start, because EDM constraints on the imaginary parts of $C_{lequ}^{(1,3)}$, C_{ledq} are prohibitive

$$v^2 |\mathrm{Im} C_{lequ}^{(1)}| \lesssim 3 \times 10^{-11} \qquad v^2 |\mathrm{Im} C_{lequ}^{(3)}| \lesssim 1 \times 10^{-11} \qquad v^2 |\mathrm{Im} C_{ledq}| \lesssim 3 \times 10^{-11}$$

de Vries et al arXiv:1809.09114
Dekens et al arXiv: 1810.05675

D parameter scenario #3

$$D \approx \kappa_D \,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde\epsilon_S\tilde\epsilon_T^*) - \tilde\epsilon_R\tilde\epsilon_L^*\right]$$

$$\tilde\epsilon_L = -\frac{\mathrm{v}^2}{2}C_{\phi e\nu}$$

$$\tilde\epsilon_R = -\frac{\mathrm{v}^2}{2V_{ud}}C_{e\nu ud}$$

$$\tilde\epsilon_S = \frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd}V_{ud} - C_{l\nu uq}\right]$$

$$\tilde\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd}V_{ud} + C_{l\nu uq}\right]$$

$$\tilde\epsilon_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$

$$\begin{aligned}\mathscr{L}_{\rm EFT} \supset\; & iC_{\phi ud}HD_\mu H(u^c\sigma^\mu\bar d^c) && + iC_{\phi e\nu}H^\dagger D_\mu H^\dagger(e^c\sigma^\mu\bar\nu^c)\\ & + C^{(3)}_{lequ}(\bar l\bar\sigma_{\mu\nu}\bar e^c)(\bar q\bar\sigma^{\mu\nu}\bar u^c) && + C^{(3)}_{l\nu qd}(\bar l\bar\sigma^{\mu\nu}\bar\nu^c)(\bar q\bar\sigma_{\mu\nu}\bar d^c)\\ & + C^{(1)}_{lequ}(\bar l\bar e^c)(\bar q\bar u^c) && + C^{(1)}_{l\nu qd}(\bar l\bar\nu^c)(\bar q\bar d^c)\\ & + C_{ledq}(\bar l\bar e^c)(d^c q) && + C_{l\nu uq}(\bar l\bar\nu^c)(u^c q)\\ & && + C_{e\nu ud}(e^c\sigma^\mu\bar\nu^c)(u^c\sigma_\mu\bar d^c)\\ & + \mathrm{hc} && \end{aligned}$$

This scenario does not have the EDM problem, because the neutral curent from the scalar and tensor operators with RH neutrinos do not generate $\bar e e\bar q q$ terms. Moreover, constraints on $\tilde\epsilon_{S,T}$ from beta decay are less stringent, at the percent level, because of the lack of interference with SM amplitudes

However it has the pion decay problem ...

D parameter scenario #3

$$D \approx \kappa_D \,\mathrm{Im}\Big[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\Big]$$

$$\tilde{\epsilon}_L = -\frac{\mathrm{v}^2}{2}C_{\phi e\nu}$$

$$\tilde{\epsilon}_R = -\frac{\mathrm{v}^2}{2V_{ud}}C_{e\nu ud}$$

$$\tilde{\epsilon}_S = \frac{\mathrm{v}^2}{2V_{ud}}\Big[C^{(1)}_{l\nu qd}V_{ud} - C_{l\nu uq}\Big]$$

$$\tilde{\epsilon}_P = -\frac{\mathrm{v}^2}{2V_{ud}}\Big[C^{(1)}_{l\nu qd}V_{ud} + C_{l\nu uq}\Big]$$

$$\tilde{\epsilon}_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$

$$\begin{aligned}\mathscr{L}_{\rm EFT} \supset\; & iC_{\phi ud}HD_\mu H(u^c\sigma^\mu\bar{d}^c) && + iC_{\phi e\nu}H^\dagger D_\mu H^\dagger(e^c\sigma^\mu\bar{\nu}^c)\\ & + C^{(3)}_{lequ}(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) && + C^{(3)}_{l\nu qd}(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)\\ & + C^{(1)}_{lequ}(\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) && + C^{(1)}_{l\nu qd}(\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)\\ & + C_{ledq}(\bar{l}\bar{e}^c)(d^c q) && + C_{l\nu uq}(\bar{l}\bar{\nu}^c)(u^c q)\\ & && + C_{e\nu ud}(e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu\bar{d}^c)\\ & + \mathrm{hc} \end{aligned}$$

The problem here is that this scenario generically predicts $\tilde{\epsilon}_S \sim \tilde{\epsilon}_P$
and from measure $\mathrm{Br}(\pi \to e\nu)$ **one has** $|\tilde{\epsilon}_P| \lesssim 10^{-5}$

$$D \sim 10^{-6}\kappa_D \mathrm{Im}\left[\left(\frac{\tilde{\epsilon}_T}{10^{-1}}\right)\left(\frac{\tilde{\epsilon}_S}{10^{-5}}\right)\right] \Rightarrow |D| \lesssim 10^{-6}$$

D parameter scenario #3

$$D \approx \kappa_D \,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\right]$$

$$\tilde{\epsilon}_L = -\frac{\mathrm{v}^2}{2}C_{\phi e\nu}$$

$$\tilde{\epsilon}_R = -\frac{\mathrm{v}^2}{2V_{ud}}C_{e\nu ud}$$

$$\tilde{\epsilon}_S = \frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd}V_{ud} - C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd}V_{ud} + C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$

$$\begin{aligned}\mathscr{L}_{\mathrm{EFT}} \supset\ & iC_{\phi ud}HD_\mu H(u^c\sigma^\mu\bar{d}^c) + iC_{\phi e\nu}H^\dagger D_\mu H^\dagger(e^c\sigma^\mu\bar{\nu}^c)\\ & + C^{(3)}_{lequ}(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) + C^{(3)}_{l\nu qd}(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)\\ & + C^{(1)}_{lequ}(\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) + C^{(1)}_{l\nu qd}(\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)\\ & + C_{ledq}(\bar{l}\bar{e}^c)(d^c q) + C_{l\nu uq}(\bar{l}\bar{\nu}^c)(u^c q)\\ & + C_{e\nu ud}(e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu\bar{d}^c)\\ & + \mathrm{hc}\end{aligned}$$

Additional constraint is provided by the fact that the gauge invariant operators, contribute to the neutrino masses and neutrino magnetic moment, which requires fine-tuning unless $\mathrm{v}^2|C_{l\nu qd,l\nu uq}| \lesssim 10^{-3}$

D parameter scenario #4

$$D \approx \kappa_D \, \mathrm{Im}\Big[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\Big]$$

$$\tilde{\epsilon}_L = -\frac{\mathrm{v}^2}{2} C_{\phi e\nu}$$

$$\tilde{\epsilon}_R = -\frac{\mathrm{v}^2}{2V_{ud}} C_{e\nu ud}$$

$$\tilde{\epsilon}_S = \frac{\mathrm{v}^2}{2V_{ud}}\Big[C^{(1)}_{l\nu qd}V_{ud} - C_{l\nu uq}\Big]$$

$$\tilde{\epsilon}_P = -\frac{\mathrm{v}^2}{2V_{ud}}\Big[C^{(1)}_{l\nu qd}V_{ud} + C_{l\nu uq}\Big]$$

$$\tilde{\epsilon}_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$

$$\begin{aligned}\mathscr{L}_{\rm EFT} \supset\ & iC_{\phi ud} HD_\mu H(u^c\sigma^\mu \bar{d}^c) & & + iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c\sigma^\mu\bar{\nu}^c)\\ & + C^{(3)}_{lequ}(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) & & + C^{(3)}_{l\nu qd}(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)\\ & + C^{(1)}_{lequ}(\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) & & + C^{(1)}_{l\nu qd}(\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)\\ & + C_{ledq}(\bar{l}\bar{e}^c)(d^c q) & & + C_{l\nu uq}(\bar{l}\bar{\nu}^c)(u^c q)\\ & & & + C_{e\nu ud}(e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu\bar{d}^c)\\ & + \mathrm{hc} & & \end{aligned}$$

From the EFT point of view, scenario 4 looks promising, because model-independent constraints on the highlighted operators are relatively mild.

In particular, from $\mathrm{Br}(W \to e\nu)$ **one gets** $\mathrm{v}^2|C_{\phi e\nu}| \lesssim 0.3$

while $pp \to e\nu$ **at the LHC leads to** $\mathrm{v}^2|C_{e\nu ud}| \lesssim \mathcal{O}(0.01)$

At loop level, there is a quadratic in $C_{e\nu ud}$ **contribution to the 4-quark EDM operator, but in this case we gain the loop and quadratic suppressions**

D parameter scenario #4

$$D \approx \kappa_D \, \mathrm{Im}\Big[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S \epsilon_T^* + \tilde\epsilon_S \tilde\epsilon_T^*) - \tilde\epsilon_R \tilde\epsilon_L^*\Big]$$

$$\tilde\epsilon_L = -\frac{\mathrm{v}^2}{2} C_{\phi e\nu}$$

$$\tilde\epsilon_R = -\frac{\mathrm{v}^2}{2V_{ud}} C_{e\nu ud}$$

$$\tilde\epsilon_S = \frac{\mathrm{v}^2}{2V_{ud}}\Big[C^{(1)}_{l\nu qd} V_{ud} - C_{l\nu uq}\Big]$$

$$\tilde\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\Big[C^{(1)}_{l\nu qd} V_{ud} + C_{l\nu uq}\Big]$$

$$\tilde\epsilon_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$

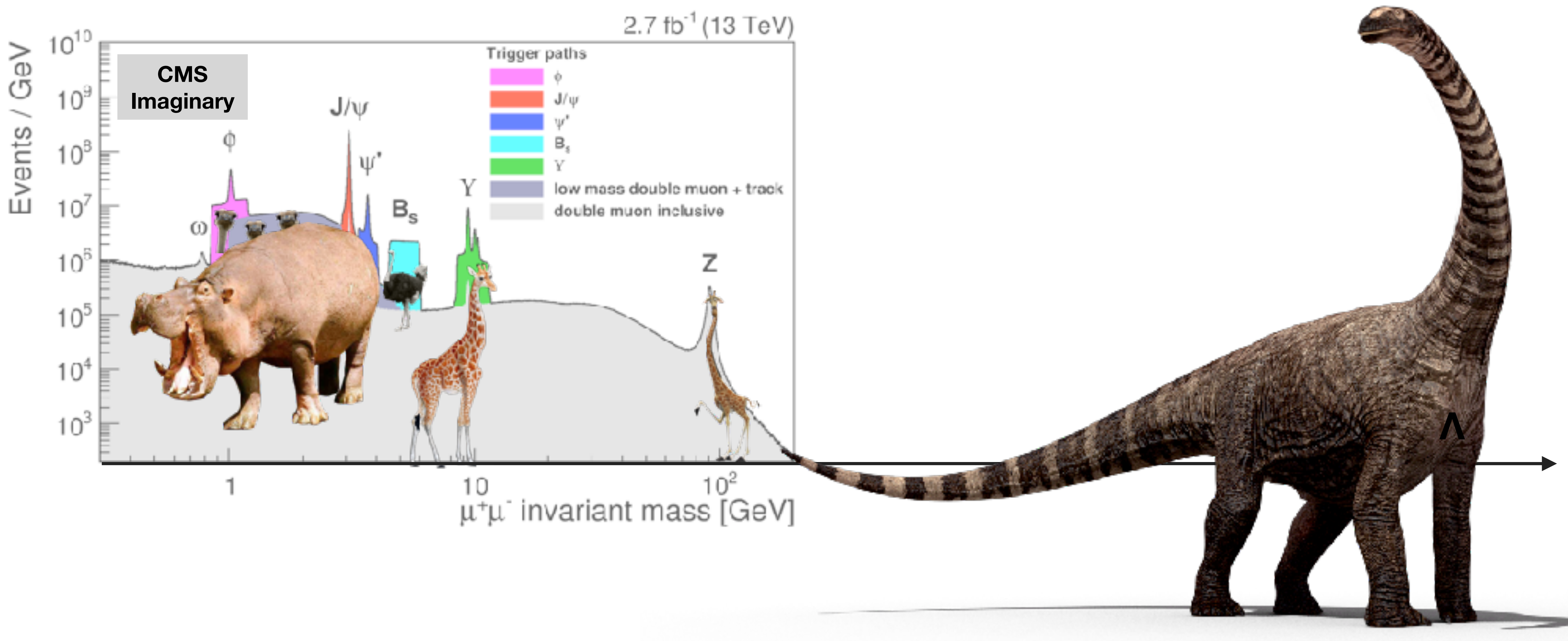
$$\begin{aligned}\mathscr{L}_{\mathrm{EFT}} \supset\; & iC_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar d^c) && + iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar\nu^c)\\ & + C^{(3)}_{lequ} (\bar l \bar\sigma_{\mu\nu} \bar e^c)(\bar q \bar\sigma^{\mu\nu} \bar u^c) && + C^{(3)}_{l\nu qd} (\bar l \bar\sigma^{\mu\nu} \bar\nu^c)(\bar q \bar\sigma_{\mu\nu} \bar d^c)\\ & + C^{(1)}_{lequ} (\bar l \bar e^c)(\bar q \bar u^c) && + C^{(1)}_{l\nu qd} (\bar l \bar\nu^c)(\bar q \bar d^c)\\ & + C_{ledq} (\bar l \bar e^c)(d^c q) && + C_{l\nu uq} (\bar l \bar\nu^c)(u^c q)\\ & && + C_{e\nu ud} (e^c \sigma^\mu \bar\nu^c)(u^c \sigma_\mu \bar d^c)\\ & && + \tilde C_8 (e^c \sigma^\mu \bar\nu^c)(\bar q H^\dagger \sigma_\mu H^\dagger q)\\ & + \mathrm{hc} && \end{aligned}$$

Much as in scenario 1, one can trade one dimension-6 operators for a dimension-8 one leading to the same interaction below the electroweak scale.
The advantage is that the latter can be generated in lepoquark models,
the disadvantage is that $D \sim \frac{\mathrm{v}^6}{\Lambda^6}$ so new physics has to be very light

D parameter scenarios

Scenario	νWEFT	νSMEFT	max $\|D\|$
I	ϵ_R	$HD_\mu H u^c \sigma^\mu \bar{d}^c$ $[(\bar{l}H\bar{\sigma}_\mu H l)(u^c\sigma^\mu \bar{d}^c)]$	$\mathcal{O}(10^{-6})$
II	$\epsilon_S,\ \epsilon_T$	$(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c),\ (\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c),\ (\bar{l}\bar{e}^c)(d^c q)$	$\mathcal{O}(10^{-14})$
III	$\tilde{\epsilon}_S,\ \tilde{\epsilon}_T$	$(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c),\ (\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c),\ (\bar{l}\bar{\nu}^c)(u^c q)$	$\mathcal{O}(10^{-6})$
IV	$\tilde{\epsilon}_L,\ \tilde{\epsilon}_R$	$H^\dagger D_\mu H^\dagger e^c \sigma^\mu \bar{\nu}^c$ $[e^c\sigma^\mu\bar{\nu}^c\bar{q}H^\dagger\sigma_\mu H^\dagger q],\ (e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu\bar{d}^c)$	$\mathcal{O}(10^{-4})$

Fantastic Beasts and Where To Find Them



THANK YOU